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AN ASSESSMENT OF PROBLEMS RELATING TO THE SOURCE, TRANSFER AND FATE OF SEDIMENT ALONG THE MACKENZIE RIVER, NWT

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PREFACE

This report was commissioned by the Inland Waters Directorate of the Conservation & Protection Division of Environment Canada, through the Department of Supply and Services (DSS), under DSS Contract No. KE144-7-4155/01-SS. The Scientific Authority for the project was Dr Terry Day, Head, Sediment Survey Section, Water Resources Branch, Inland Waters, Ottawa.

The purpose of the study was to provide the Inland Waters Directorate with a thorough assessment of "sediment concerns" on the Mackenzie River between Great Slave Lake and Point Separation, prior to further sediment monitoring and study activities. The terms of reference required identification of concerns, review of existing information relating to them, assessment of the adequacy of this information, and recommendations for further work.

The report is organized in three parts. Part One provides a background to the study, a description of the Mackenzie river system, and a summary of the eleven sediment issues identified. Part Two then addresses, one by one, each of these issues, together with a review of the relevant information, an assessment of its adequacy and recommendations for additional work. The first five issues deal with suspended sediment; the last six with bed material.

Part Three provides a summary of the various recommendations, together with some indication of their priority, and suggestions regarding the timing of their implementation.

Throughout, the work has benefitted considerably from the assistance and support of Dr Terry Day, the Scientific Authority, and Jack Wedel, Head, Water Planning and Management Branch, Inland Waters Directorate, Yellowknife, and this is duly acknowledged.

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The diversity of interests represented in this list above is itself some indication of the breadth of issues related to sediment movement and accumulation along the Mackenzie.

AN ASSESSMENT OF PROBLEMS RELATING TO THE SOURCE, TRANSFER AND FATE OF SEDIMENT ALONG THE MACKENZIE RIVER, NWT

Executive Summary

This report describes, in some detail, the major issues related to sediment transport along the Mackenzie River downstream of Great Slave Lake. It is organized in three parts.

Part One provides a background to the study, describes the general character of the Mackenzie river, and summarizes the eleven sediment-related issues identified. Part Two deals with each of these eleven concerns, individually, according to the following format: the issue itself; information needs for addressing the issue; adequacy of existing information available; and recommendations for further work necessary to remedy deficiencies in current knowledge. Part Three provides a summary of the recommendations (with some indication of their priorities) and a list of publications consulted in the work.

Eleven major issues are identified. The first five deal with sediment tranported in suspension by the Mackenzie; the last six concern sediment found on the river bed. There is some degree of linkage between the two groups of problems, because some of the material on the river bed actually moves in suspension at high flows. Most of the suspended load, however, is not derived from the river bed. The eleven issues are:

1. the magnitude, timing and spatial pattern of influx of suspended sediment from the river to the Beaufort Sea: these are key factors controlling the offshore sediment plume (and its relationship to marine productivity), rates of infill of pipeline trenches, seabed stability etc.;

2. inputs of suspended sediment to the Mackenzie Delta as this affects the rate of build-up of the Delta surface - a crucial issue in view of fears of future submergence of the Delta with increasingly rapid rates of local sea level rise and possible permafrost degradation due to global warming;

3. the magnitude, timing and spatial pattern of nutrient supply to the Delta and the Beaufort Sea, bearing in mind that much of the nutrient load is bound to the fine-grained suspended load of the river;

4. the transport of contaminants (hydrocarbons, heavy metals etc.) to the Delta and the Beaufort Sea, many of which are also moved primarily in association with the fine-grained fraction of the suspended load;

5. identification of the main tributary sources of the suspended load of the Mackenzie, so that the impact of land use changes in these tributaries (e.g. damming of the Liard for hydro power) on the inputs of sediment, nutrients and contaminants at the mouth of the Mackenzie can be assessed in advance of the changes;

6. transport rates of bed material along the channel floor of the Mackenzie, partly to enable calculation of inputs to the Delta (and hence allow assessment of the stability of Delta channels in the years ahead), but more generally to provide a scientific basis for answering more specific issues considered next (7-11) that hinge on the rate of transport of bed material in the channel;

7. shoaling of sediment in key reaches of the Mackenzie bed, as it affects navigation and the need for channel dredging- especially in relation to the increased traffic in the years ahead associated with oil and gas development;

8. the need to acquire a better understanding of the processes of scour and fill of the bed and banks, under ice and breakup conditions, especially in relation to the stability of pipeline crossings of the mainstem;

9. the need to acquire a better understanding of the role of shoals of sandy bed sediment in localizing ice jams during spring breakup, with the goal of eliminating, reducing or at least predicting, flooding associated with such ice jams;

10. the rapid expansion of the artifical islands at Norman Wells by trapping of sediment, and the implications of this for navigation and ice jams in the local area;

11. the environmental consequences of possible extraction of large quantities of granular material from the bed of the Mackenzie, particularly in connection with pipeline construction along the valley axis.

Recommendations are made for future work needed to supplement existing data in order to address the issues raised above. The major recommendations may be summarised as follows:

(a) an immediate, in-depth, review of the data for the five main sediment stations on the lower Mackenzie system, to establish whether or not sufficient data exist to develop numerical models for the prediction of suspended sediment loads (broken down by particle size and timing) at these sites from routinely collected hydraulic data such as discharge, water temperature etc.; this will enable decisions to be taken as to whether

routine sampling can be terminated at these stations, allowing redeployment of resources elsewhere;

(b) a similar analysis of annual loads of bed material sediment in key reaches of the river by analysis of bathymetric charts in areas where repeat surveys have been undertaken by the Canadian Hydrographic Service;

(c) following (b), resurveys of key reaches of the river to allow updating of data to the 1980's, and to rectify gaps in the data file;

(d) following (a), addition of new sediment stations to the Mackenzie network allowing routine monitoring of suspended material in key reaches: Wrigley, Norman Wells and Fort Good Hope, and at the mouths of the three main Delta channels;

(e) following (d), once the sediment regime at these new stations has been established, expansion of the programme at these sites to include nutrients, hydrocarbons and heavy metals;

(f) an increase in basic research into ice-jamming in relation to shoaling and into the effects of an ice cover on bed scour.

Above all, an agency should be established to ensure full coordination of sediment and water-related issues in the Mackenzie basin downstream of Great Slave Lake. At the present time, it is apparent that many agencies are pursuing investigations into water and sediment in the Mackenzie corridor without appreciating that their work is related, often intimately, to other studies by other agencies. In addition, much of the data collection is not standardized among different agencies, with different techniques of sampling, storage and analysis; as a consequence, results are often difficult to compare.

It is also readily apparent that, while acquisition of sediment data in the North is expensive, and while it often cannot be justified on the basis of a single agency's concerns, sediment issues in the Mackenzie touch so many different departments that failure to acquire the data cannot be justified either. The obvious solution is greater cooperation among departments, and some form of inter-departmental (including private enterprise) cost-sharing.

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PART ONE

1. INTRODUCTION

1.1 BACKGROUND

The Mackenzie River network, draining an area in excess of 1.8 million square kilometres, is the largest catchment in Canada. The full length of its longest watercourse, from the headwaters of the Finlay River west of the Rocky Mountains in British Columbia, to the Mackenzie Delta on the shores of the Beaufort Sea, is over 4,000 kilometres.

The present report deals only with the lower basin of the Mackenzie River system: the Mackenzie River itself, from Great Slave Lake to the Beaufort Sea, a distance of just over 1,700 km. The terms of reference of this report stipulate a focus on the 1,500 km reach between Great Slave Lake and the start of the Mackenzie Delta at Point Separation, but, since so many of the issues identified in this reach have repercussions downstream, the Delta, and indeed the inner Beaufort Sea itself, must be included.

The mainstem Mackenzie and its tributaries represent a major resource to those who work and live in this region. Fish provide a source of food to native people throughout the year. The Mackenzie has also long been the transportation artery through the region, with a barge service operating from early June to late October, from the town of Hay River on the shores of Great Slave Lake to the Arctic Ocean. The potential for hydro-electric power generation, especially on its major tributary, the Liard, is enormous. The sediments transported by the Mackenzie have built up the second largest delta system in North America, with a subaerial extent of almost 13,000 square kilometres. Nutrients supplied by the Mackenzie River play a vital role in maintaining the Delta ecosystem, a system that has been central in the lifestyle of the local native peoples of the area. The sediment and nutrients from the Mackenzie similarly exert a large influence on the physical, chemical and biological character of the coastal areas of the Beaufort Sea.

Twentieth century development in the region has seen the production of oil at Norman Wells, and the mining of various metal ores in tributary basins of the river. Oil has been refined at Norman Wells since the 1930's. Discovery of oil and gas at Prudhoe Bay on the Beaufort Sea coast of Alaska, and in the Mackenzie Delta area, led to applications in 1974 for a pipeline along the full length of the Mackenzie Valley. A 10-year moratorium was placed on this in 1977 by the Mackenzie Valley Pipeline Inquiry under Mr Justice Thomas R. Berger. More recently, Esso Resources Limited and Interprovincial Pipeline Limited applied to install an oil pipeline from Norman Wells to the refinery at Zama Lake in northern Alberta; this was completed in 1985. Plans continue to be made for pipelines from the Delta, along the northeastern side of the Mackenzie Valley past Fort Simpson, and then crossing to the south.

It is primarily in the light of this planned increase in activity, associated with hydrocarbon development, that the present review should be seen. Detailed studies of the impact of pipeline development on northern hydrology were published in the mid-1970's by the Environmental-Social Committee, Northern Pipelines Task Force on Northern Oil Development. Hydrocarbon production in the region did not proceed as rapidly as anticipated, but significant increases are impending.

1.2 HISTORY OF SEDIMENT OBSERVATIONS IN THE MACKENZIE RIVER AND ITS TRIBUTARIES

Though investigations of sediment transported by rivers in Canada were undertaken as long ago as 1948 (to meet the needs of federal and provincial agencies for assessment of particular projects), it was not until 1961 that a systematic survey was undertaken by the Water Resources Branch. Since that time, a major goal of the sediment survey program has been the routine collection and provision of data related to sediment transport, throughout the country, for applications in water resource engineering, water quality and environmental studies.

In the lower Mackenzie basin, water level gauges (for the determination of water discharge) were located at several sites, primarily as an aid in forecasting water levels for navigation purposes. Sediment sampling was not begun until 1972, at the time of widespread hydrological research in the basin noted above. Stations have been operated on the main stem upstream of the Liard confluence and at Norman Wells, but the only one currently operated is just upstream from Arctic Red River. Data have been collected on major tributaries - the Redstone, Arctic Red and the Peel River - but the only station that is currently maintained is that on the Liard near its mouth. Moreover, sampling on the Liard in the 1980's has been largely dependent upon funding by BC Hydro, stemming from that agency's interest in possible hydro-electric development further upriver. Several short term programmes were undertaken on minor tributaries in the mid-1970's as part of general scientific enquiry in the hydrology of small northern watersheds: the Harris, the Martin and the Trout rivers. Data were also collected on six distributary channels of the Delta in 1974 and 1975.

With the exception of the Liard near its mouth, and the Mackenzie upstream of Arctic Red, data for the concentration and loads of suspended sediment are meagre. This is even more true of the physical (grain size) and chemical (nutrients, contaminants etc.) characteristics of the suspended sediment. Data relating to bed material characteristics of the Mackenzie and its tributaries are also sparse, and information on rates of bed material transport are virtually non-existent.

With this background, and especially in light of planned increases in hydrocarbon production in the years ahead,

previously noted, the terms of reference of this report are readily appreciated.

1.3 TERMS OF REFERENCE

The aim of this study was to provide a thorough assessment of "sediment concerns" along the Mackenzie River, their data and information requirements, and the adequacy of the existing data base. The work was commissioned by the Inland Waters Directorate in order to provide that agency with an appropriate framework within which future sediment monitoring and study activities could be planned.

The specific tasks stipulated were:

(a) to identify sediment problems along the Mackenzie River between its origins in Great Slave Lake and Point Separation;

(b) to identify the data and information demands for addressing the problems identified;

(c) to assess the adequacy of the existing available data for these purposes; and

(d) to provide recommendations for further monitoring and studies required to satisfactorily address the problems identified.

This introduction is followed by a brief outline of the development of the Mackenzie River during post-glacial time and a rather longer description of the different reaches of the river between Great Slave Lake and the Delta. This section may be omitted by the general reader, but the reach descriptions should prove valuable to anyone concerned with details of bed material transport along the Mackenzie. The third section of Part One summarizes the eleven sediment issues identified and is intended as an overview of the work.

In Part Two, each issue is examined in turn, adopting the fourfold format described above. To a large extent, each section stands on its own, but inevitably there are interactions among the issues, and there is therefore some cross-referencing between sections.

A summary of the recommendations, arranged in order of priority in terms of actual execution of the work, is provided in Part Three.

2. THE MACKENZIE RIVER

2.1 POST-GLACIAL EVOLUTION

The present Mackenzie river, like many rivers in Canada, has developed much of its course in the last 10,000 years or so: in the period following the disappearance of the last glacial ice mass that covered Canada. This is important to remember, because the present day behaviour of the river is, to some extent, a continuation of processes that have been operating in the last few thousand years.

According to Prest (1969), the last continental ice cap to cover Canada (late Wisconsinan) abutted the eastern margins of the Mackenzie Mountains, thus covering the full length of the Mackenzie Valley. With melting of the ice mass, retreat of its western margin began about 14,000 years ago, exposing that part of the valley downstream from Camsell Bend (Fig.1: km 460) by 11,000 BP (years before present).

This emergence of the Mackenzie Valley area, from beneath the ice cap, was a complex process because lobes of the ice margin temporarily blocked drainage of meltwater, impounding lakes in the valley area. The detailed history of lake development and disappearance is extremely difficult to reconstruct. Evidence exists, however, for lacustrine water in the Mackenzie valley, immediately upstream of the Ramparts, by 11,500 BP; and in the area upstream of Fort Simpson several thousand years later. The latter area of submergence was part of a huge water body, called by Craig (1965) Glacial Lake McConnell, which encompassed Great Bear Lake, Great Slave Lake and Lake Athabaska.

Irrespective of the details of this period, the essential point is that large amounts of sediment accumulated in these lakes. Subsequently, as the ice margin shifted further east, and as the land continued to rebound from its earlier depression under the weight of the ice cap, the lakes were able to drain. Upstream of the Ramparts, then, the Mackenzie River has been downcutting through lacustrine sediments over much of post-glacial time. Mackay and Mathews (1973), for example, described a cliff section at km 1041 on the Mackenzie (near Hardie Island) that is 50 m tall, and made up of sediment (mostly lacustrine silt and clay) through which the river has cut in the last 6,000 years. In places, the degrading river has encountered bedrock; this has retarded the downcutting process upstream of the outcrop, but not downstream, resulting in the creation of rapids e.g. Sans Sault Rapids.

Downstream of the Ramparts, post-glacial development has been quite different. Mackay and Mathews (1973) have shown that the present course of the river there coincides with a deep bedrock trench as far downstream as the Lower Ramparts (just

upstream of Arctic Red River). The trench originates east of the Franklin Mountains, underlies the Hare Indian River, and joins the Mackenzie at Fort Good Hope (Fig. 2). It is believed to represent a preglacial course of the Mackenzie River. The 15-20 km wide trench is certainly older than the time of the last Wisconsinan ice cover. The trench still contains glacial and alluvial deposits at its sides, indicating that it was infilled to at least 80 metres thickness in many places; its floor is generally below present sea level, by about 20 m in the Fort Good Hope area.

With the emergence of the Mackenzie Valley from beneath the last cover of glacial ice, and the settling of sediment in the lake areas upstream of the Ramparts, meltwater was able to cut down through these older deposits in the trench. Later, as the lakes upstream gradually drained, and the resultant river started to incise the former lake bed deposits, increasing quantities of sediment began to enter the Fort Good Hope trench, leading to deposition (aggradation) of sediment.

Mackay and Mathews (1973) summarize this contrast in development upstream and downstream of the Ramparts as follows.

> "Even now, erosion still dominates in the lowlands above the Ramparts, whereas an aggrading to graded condition persists below."
>
> "Upstream from the Ramparts, tributaries are graded near their mouths, whereas downstream, the tributaries are aggraded, and may have drowned or oversized mouths."
>
> "Upstream, some of the islands in Mackenzie River extend high above the limits of modern flooding, and are well wooded with spruce and poplar; downstream, the islands are lower, subject to flooding, and spruce is far less abundant."
>
> "Upstream, for at least 250 km, there is no sign of a former interglacial or preglacial channel, and the Mackenzie River wanders across or is cut into a broad plain; downstream, the river is confined within a rock-rimmed trench."

These comments of Mackay and Mathews provide a useful framework within which to view present processes operating in the Mackenzie Valley. In many cases, however, a more detailed description of the river's course is essential. This is especially true in examining movement of bed material along the river. Such a description is provided next. The general reader should bypass this section, and proceed directly to the summary of issues (Section 3). Section 2.2 will, however, prove useful for anyone concerned with navigation problems on the Mackenzie, areas of potential riverbed borrow material, etc., and such

readers may wish to refer back to it when examining those parts of the report (Sections 6-11).

2.2 REACHES OF THE MACKENZIE RIVER

The Mackenzie River comprises distinct reaches, of variable length, in its course from Great Slave Lake to Point Separation. The following subdivision is based on the channel pattern and on changes in the long profile. The former is indicated by 1:50,000 bathymetric charts (Canadian Hydrographic Service, 1983). The latter are obtained from the vertical survey undertaken by the Geodetic Survey of Canada as part of the investigation by Public Works Canada (1976) for proposed navigation channel improvements. These elevation data refer to low water datum, defined as the water level corresponding to the 10% stage duration, i.e., for which water level is above the stage 90% of the time during the navigation season. All gradients below are expressed in units of metres fall per 100 km horizontal distance. The Public Works Canada report also provides information on bed material in key areas of proposed dredging.

In general, there is strong agreement between points where channel pattern alters and where breaks of slope occur in the long profile. The resultant reaches also tend to corresond to distinct tracts of valley in terms of the regional pattern of surficial deposits mapped by Hughes et al. (1973) and Rutter et al. (1973). Twenty reaches are identified below. They were defined without knowledge of the subdivision provided by Galay (1978). Subsequent comparison shows strong correspondence between the two systems, though occasionally two successive reaches in one system are grouped as a single reach in the other, and the location of reach boundaries between Fort Norman and Norman Wells is quite different. The relevant Canadian Hydrographic Chart numbers are indicated in parenthesis for each reach.

A map of the reaches is provided in Fig. 3; the long profile of the upper and middle parts of the river is given in Fig. 4a,b; insufficient data exist to construct the profile downstream of Fort Good Hope.

Reach 1. km 0 - km 60: Beaver Lake Basin (6404)

This is a small till-mantled rock basin receiving the outflow from Great Slave lake. Soundings in mid-lake indicated "very soft grey silt-clay", but the entry channels to Beaver Lake, and the exit, are underlain by a firm brown sandy, clayey silt till (60-90% silt and clay) with gravel size clasts usually less than 25 mm. Mean gradient is 6.9 m per 100 km.

Reach 2. km 60 - km 80: Providence Rapids (6405)

This is a steep till-mantled bedrock reach connecting Beaver lake basin to the Mills Lake flats. Average gradient is 42.8, the steepest of all twenty reaches. The till is similar to that in reach 1, but winnowing of fines by strong currents has left a lag of gravel in many places up to "boulder" size.

Reach 3. Km 80 - km 225: Mills Lake flats (6405-06-07)

This is a very gentle reach (mean gradient of 3.8) dominated by broad but shallow Mills Lake at the start, and then a 90 km stretch of narrow but deeper flow to the "Head of the Line". The reach downstream of Mills Lake shows up clearly on the surficial geology maps as a broad swath of alluvium about 10 km wide. Long-term degradation of the reach has lowered the outflow from Mills Lake, and exposed large swampy flanking areas of the former lake bottom. Bed material in the narrow reach is unknown. Some sand deposits are found in shallow near-bank areas.

Reach 4. Km 225 - km 300: Jean Marie narrows (6407-08)

This is a much steeper (16.3), narrower (about 500 m) and deeper reach extending as far as Rabbitskin River. The thalweg is freqently 10-15 m deep at low water datum. The channel appears to be cut in sandier till, with varying degrees of gravel clasts. Silt-clay contents in boreholes ranged 10-48%; sand ranged 25-73%; gravel was 13-52% and up to "cobble and boulder size". Valley flanks throughout the reach are part of a glaciolacustrine plain.

Reach 5. Km 300 - km 327: Green Islands Rapids reach (6409)

This is even steeper than the previous reach (37.6) but broader (about 1000 m) and therefore shallower. Bed material appears to be the same sandy till as in reach 4, though frequently it has been reworked as sandy, gravelly alluvium, and in the short Green Islands Rapids cobbles and boulders are widespread. Banks in this reach are taller (20-40 m) than the reach upstream, reflecting downcutting by the river. "Cut mud banks" are marked on the CHS charts, unlike in the Jean Marie narrows, but in fact the surficial geology map indicates till throughout the right valley wall.

Reach 6. Km 327 - km 410: Liard-Mackenzie confluence reach (6410-11)

This is a substantially gentler, concave-upward, reach (mean gradient of 11.1) extending to the upstream end of Burnt Island. The bed shows signs of becoming almost entirely alluvial. However, Galay (1978) cites a report by Blench and Associates (1975) which suggests that the bed is paved with cobbles and boulders on the right side. Channel width averages about 2 km

with strong lateral separation of the two river inflows: the thalweg is generally in the right hand half of the channel (occupied by water from the upper Mackenzie), while the left half contains frequent shoals formed by sand supplied by the Liard. Both valley flanks are, again, generally indicated as part of a glaciolacustrine plain.

Reach 7. Km 410 - km 515: Camsell Bend island reach (6411-12-13)

A striking change in channel pattern occurs here: areas of sand shoals in the previous reach are now replaced by large vegetated islands, starting with Burnt Island and ending with McGern Island. The thalweg, moreover, is no longer restricted to the right half of the channel, but bifurcates and meanders from side to side. Bed material from the Liard now appears to occupy the full channel width and, for the first time, the Mackenzie bed is fully alluvial. The cause of the transformation is unknown. However, a definite break of slope occurs at the start of the reach, with the gradient decreasing to 7.8. This gradient is maintained until an abrupt steepening at the end of McGern Island.

The alluvial belt itself is also much wider in this reach, averaging about 5 km, of which the river and islands occupy about 3 km. The bed material is not entirely sand. Immediately downstream of the North Nahanni at Camsell Bend, gravel is marked on the charts at the upstream end of some islands; some of the shoals are marked as mud, and in the channels around the end of McGern Island, boreholes show till in many places. Extensive sand and gravel glaciofluvial deposits form the left bank between the North Nahanni and Root rivers. McGern Island is also indicated by Rutter et al. (1973) to be made of glaciofluvial, rather than alluvial, sediment.

A possible explanation of the transformation is that the entire reach represents the gentle upstream flank of a wedge of bed material from the North Nahanni River (km 455); the steeper, downstream flank, would, by implication, correspond with the break of slope at the end of the reach. Interestingly, Neill (1973) suggested that the wide, island-dominated character of this reach "probably results from inflow of coarse bed-load supplied by the Root and North Nahanni rivers". If this interpretation is correct, it raises the question of whether all the Liard bed material supplied from the steeper previous reach is capable of passing through the Camsell Bend reach, and whether, in fact, the Camsell Bend reach is currently aggrading.

Reach 8. Km 515 - km 680: the Wrigley reach (6413-14-15)

The river abruptly steepens between the end of McGern Island and the confluence of the Dahadinni at the end of this reach. The mean gradient is 15 m per 100 km. The river also narrows substantially, and islands become smaller, and eventually

disappear. Upstream of Wrigley River, the width averages 2 km, some islands exist and the gradient is irregular. Both valley walls are till or till-mantled. No borehole data are known but charts indicate boulders and gravel. Downstream of Wrigley River, the gradient is far more uniform, and slightly less (about 13), the width is less (about 1200 m) and islands completely absent. This lower subreach is virtually straight and bounded by tall glaciolacustrine clay banks throughout almost its full length. No bed material data are available for this lower subreach, though gravel is marked on charts at the lower end. There is a marked step-down in the long profile at the bend between Blackwater River and Dahadinni River (Fig. 4a).

The apparent absence of sand in the channel bed raises certain obvious questions. Is the start of this reach in fact the end of movement of sandy bed material from the Liard system, or does it simply indicate that such material is now being carried through the steeper and narrower Wrigley reach as wash load? Though the reach is steeper than the one upstream, it is only slightly steeper than the Liard-Mackenzie confluence reach in which sandy bed material first dominates the main stem.

Reach 9. Km 680 -km 715: <u>the Dahadinni-Redstone reach</u> (6415)

A further steepening occurs in this short reach with a mean gradient of 28.5. It corresponds to a slight widening of the river and the presence of several large islands. Charts show gravel bed material with some sand in places. But rock is also exposed and boreholes show till-like material. Both valley walls are till-mantled. The reach appears to be only partly alluvial.

Reach 10. Km 715 - km 790: <u>the Redstone-Keele gravel fan</u> (6415-16)

The onset of this reach is marked by an abrupt increase in local slope to 43 m per 100 km, gradually decreasing downstream. The mean gradient is slightly less than in the previous reach at about 23, and the river is distinctly multi-channel around well-developed islands, some of which are 5 to 6 km in width. Charts show gravel as the main bed material with only isolated sand tracts in backwater areas. This reach appears to be the gravel fan of the Redstone and Keele bed load inflows. It ends very abruptly at Seagull Island with a dramatic decrease in gradient to 9.1. Gravel does not appear to travel past this point.

The last comment would seem to imply that the reach is one of aggradation. Galay (1978) appears to have come to this conclusion. He remarks that the reach is probably the most unstable one along the entire Mackenzie River. "The river slope through this reach", he continues, "has increased considerably, probably due to the buildup of sediment at the upper end of the reach." He also emphasizes that the Redstone River seems to supply much more load, both bed material and wash load, than the Keele. Whether the reach is, in fact, aggrading, in an absolute

sense, is not clear. Certainly during post-glacial time the entire river bed as far as Fort Good Hope has been degraded, and the increased slope here might also be due to the more rapid degradation of the Mackenzie in the next reach downstream

Reach 11. Km 790 - km 965: the Redstone-Keele sand reach (6416-17-18-19)

The markedly lower gradient in this reach (9.1) is fairly uniform throughout its 175 km length apart for a small hump in the profile at Fort Norman. The river is still dominated by islands surrounded by large shallows, but the appearance is quite different from the reach upstream: rather than narrow multiple channels, the low water map indicates a broad single channel with the thalweg splitting around isolated islands. Gravel seems to be absent, except at the mouth of the Little Bear River, and the subreach upstream of Norman Wells is dominated by sand, according to CHS charts and soundings done by Public Works..

Downstream of Norman Wells, although there is no change in gradient or in planform appearance, the Great Bear River (which carries little sediment) tends to keep the right half of the channel freer of sandy shoals, and the thalweg tends to stay on the right side. The bed material on the right side of the river is not known in most places, but at Norman Wells borings show that this side of the river is underlain by in-situ clay. Considerable sand and gravel deposits were found in this general area as part of the Norman Wells Expansion Project, though the exact sites are not known. Valley walls are either till or glaciolacustrine clay. Till-like material has been cored towards the downstream end of the reach on the right side near Rader Island and Judith Island and presumably underlies the clay near Norman Wells. This subreach therefore resembles the Liard-Mackenzie confluence reach in that it is not entirely alluvial, though its appearance is dominated by the presence of large sandy islands. The reach ends at Patricia Island.

Reach 12. Km 965 - km 1014: Axel Island sand flats (6419-20)

The river narrows appreciably in the first part of this reach, flanked by the Carcajou Range on the right hand side and glaciolacustrine clay banks on the left. Islands are absent, except just above the Sans Sault Rapids where the channel broadens to over 5 km around Axel Island. The gradient is also substantially less, averaging only 3.6 m per 100 km over the reach. However, most of this fall is in the first part of the reach around Svenson Shoal; the GSC survey then indicates that the rest of the reach averages only 2.0 m per 100 km. The overall reach gradient is thus less than that in Mills Lake flats and the main part of this reach is gentler than any place on the mainstem Mackenzie above Point Separation. Indeed, this gradient of 2.0 is only slightly higher than the late summer water slope

from Point Separation to the mouth along Middle Channel, given by Lewis (in prep.) as 1.6.

Over most of the reach, the river is more than 10 m deep along the thalweg at low water datum, but it is doubtful if this increased depth could counter the very low gradient sufficiently to ensure continued transport through the reach of all sandy bed material from upstream. The implication is that the reach is one of aggradation. The end of the reach coincides with the entry of Mountain River to the Mackenzie at Sans Sault Rapids.

Reach 13. Km 1014 - km 1030: Sans Sault Rapids (6420)

This is a bedrock controlled reach with a mean gradient of 29.4.

Reach 14. Km 1030 - km 1080: the Hume Crossing shallows (6420-21)

This reach is wide, sand-bedded and shallow. Sandy bed material from the Mackenzie is transported over the Sans Sault Rapids and is supplemented by the load from the Mountain River. The latter is cut in extensive deposits of sand and gravel near its mouth. The Mackenzie itself in this reach is bounded by glaciolacustrine clay banks. The channel pattern is marked by occasional large islands and shoals. The gradient is 9.0. Both slope and appearance are similar to those of the much longer Redstone-Keele sand reach.

Neill (1973) speculated that the gravel-bedded Mountain River is probably an important supplier of coarse bed material to the Mackenzie, but only one instance of gravel is marked on the CHS chart downstream of Sans Sault Rapids, unlike the reach downstream of the Keele and Redstone Rivers.

The channel here has a well-documented post-glacial history (Mackay and Mathews, 1973) having cut down through nearly 50 m of sands and lacustrine clays in the last 6000 years. Exposures of these clays are found along both valley walls. Mackay and Mathews suggest that channel downcutting is still taking place, notwithstanding the sand-clogged appearance of the channel. The channel is particularly shallow where bends force the deep flow to cross from one side of the channel to the other as at km 1030 and km 1058.

Reach 15. Km 1080 - km 1100: Ramparts Rapids and narrows (6421)

This is a bedrock (limestone) reach with a mean gradient of 15.4, most of this drop in river level occurring in the first three kilometres.

Reach 16. Km 1100 - km 1190: Fort Good Hope trench (6422-23)

The river here enters a deep Pleistocene bedrock trench that was partially infilled with till and alluvium. Mackay and Mathews (1973) imply, on the basis of spruce root growth exposed in cut banks at the mouth of Fossil Creek (km 1105), that sedimentation there may have been occurring at a rate approaching 1 m in 200 years. This is not necessarily evidence that aggradation is currently occurring in this reach though: that these sediments have been exposed by scour, in fact, suggests the opposite.

The channel itself is weakly sinuous within the trench. In the upstream part, there are distinct outer-bank bedrock walls that are undercut, alternating with slip-off slopes of intervening meander spurs. Point bars are generally separated from the adjacent meander spur by sloughs. Mean channel width at bankfull stage is about 2000 m which would be consistent with a meander wavelength of 20-24 km. Actual wavelength is about 22 km. Amplitude gradually decreases downstream from Fort Good Hope. Insufficient data exist to indicate the mean gradient in the reach as defined here, but from the start of the reach to km 1290 (almost at the end of the next reach), the slope is 5.3 m per 100 km.

Reach 17. Km 1190 - km 1350: Little Chicago bends reach (6423-24-25)

This reach extends as far as Barrel Crossing. Valley walls are mostly till and bedrock. The main channel "meanders" more strongly, but more irregularly, than in the previous reach. Width increases to about 3300 m, but "wavelength" increases even more so than might be expected on the basis of width, to about 80 km. Depositional bars occur throughout the reach, but are not in phase with the main channel bends, and the result is a confused channel pattern. The reach takes on more the form of well-defined bends separated by straight sections. In the former, complex point bar areas exist, though the thalweg is rarely confined to the outer bank. In the latter, rudimentary pool-riffle units alternate from bank to bank, but are not as well-defined as in the next reach. Kruggel (1987, pers. comm.) identified this stretch of river as the most serious along the Mackenzie as far as shoaling is concerned.

Reach 18. Km 1350 - km 1435: the Mackenzie alternate bar reach (6425-26)

The valley walls in the first half of this reach are glaciolacustrine clay, while, in the downstream half, till is more common. The mean gradient between km 1290 and km 1453 is slightly lower than in the previous two reaches at 3.4 m per 100 km. The reach itself shows a classic pattern of alternating pool-riffle units that, in general, have crossovers corresponding to that of the navigation channel. Twelve such units have been identified with a mean inter-riffle spacing of 6800 m. This mean

value is lower than that of the "typical" unit because of two small units at a contraction in the river near Rabbit Hay River. The typical length of a pool-riffle unit is about 12 km. Previous studies of pool-riffle channels indicate that spacing averages 5 to 7 times channel width (Knighton, 1984). Bankfull width in this reach is about 2200 m which would be consistent with a pool-riffle length of 11 to 15 km.

Reach 19. Km 1435 - km 1455: Lower Ramparts bend (6426)

The pool-riffle pattern is broken by a pronounced bend, bounded by shale and limestone walls, just before the entry of Arctic Red River. Most of the channel bed is still indicated as sand on the charts. The constriction in the channel, to about 1000 m, does mean, however, that the thalweg is extremely deep (more than 20 m at low water) and the bed material there is unknown.

Reach 20. Km 1455 - km 1475: Mackenzie-Arctic Red confluence (6426-27)

This is a short straight reach to the start of channel splitting in the Mackenzie Delta at Point Separation. Valley walls are till-mantled. The river is still narrow (about 1200 m) and deep, with a weak pattern of three alternating pool-riffle units. The gradient is unknown, but if it is the same as in the main alternate bar reach (3.4), then a marked reduction in slope is implied at Point Separation, where the low water gradient to the sea is less than 1.6. In turn, this raises the question of the ability of the Mackenzie to continue transporting its bed material load through the Delta over this reduced gradient. It seems likely that aggradation begins at Point Separation, and that only part of the bed material load, probably finer in texture, is moving through the Delta channels. A more detailed long profile downstream of the Arctic Red confluence would be useful.

Comments

Previously Fox (1981) and Church et al. (1986) have identified reaches of alluvial sedimentation on the Mackenzie River. Both were based on channel pattern (multiplicity of bars, islands, etc.). Correspondence between the two is reasonable, but far from perfect. Moreover, whereas that of Fox subdivides the river into reaches of light and heavy-to-moderate deposition, that of Church et al. simply refers to zones of moderate and heavy alluvial sedimentation. There is no implication in the latter scheme that areas of heavy alluvial sedimentation correspond to heavy deposition at the present time. Neither scheme corresponds completely with the subdivision outlined in this report. This is to be expected, given that they were based on channel pattern as shown by small scale topographic sheets, and that the authors did not have available to them the detailed long profile surveyed by the Geodetic Survey of Canada.

3. SEDIMENT ISSUES: A SUMMARY

3.1 INTRODUCTION

On initial reflection, especially for those unfamiliar with the Mackenzie, it may well seem that there are few real sediment issues on this river. As Justice Berger remarked in 1977 in the opening of his report on the Mackenzie Valley Pipeline Inquiry: "The Mackenzie is one of the last great rivers that is not polluted." Notwithstanding this observation, little sediment data exist, as just noted, and given the impending transformation of the river area with hydrocarbon development, benchmark data would clearly be useful in order to assess the impacts of such development.

The need for sediment data on the Mackenzie, however, is far more urgent than simply to prepare for possible changes in the watershed's character that may, or may not, materialize in the years ahead. There are specific issues that already exist, and there are identifiable changes planned for the immediate future that are certain to have an impact on the Mackenzie. Individual government agencies are well aware of these, as they pertain to their own particular mandate. What is apparent, however, is that most agencies are not always aware of similar sediment-related issues that fall outside their own particular domain, but which, nonetheless, have repercussions that affect them in some way.

The issues that are described in Part Two of this report belong to two main groups: those that relate to relatively fine sediment that is moved in suspension, and those that relate to coarser sediment that is found on the bed of the river. Strictly speaking these two types of sediment - suspended sediment and bed material - are not mutually exclusive. To the general reader, not fully conversant with sediment transport in rivers, this is perhaps not important, and the next paragraph may be bypassed. To the specialist, however, who may be involved in the implementation of parts of this report, a few words of clarification are in order.

Much of the sediment that moves downriver in suspension is so fine that it is washed right through a river reach without settling on the bed in appreciable quantities: this is the so-called "wash load". Some part of the suspended load, however, is actually fine bed material that is temporarily suspended in the flow, at high velocities, only to be redeposited on the bed as the flow wanes. This suspended bed material, together with the coarser bed material that is moved downchannel in contact with the bed (the so-called "bed load") is usually grouped as the "bed material load". Thus two clearcut theoretical modes of separating the total sediment load of a river are possible: suspended load versus bed load; and wash load versus bed material load. In practice, it is usually much easier to measure suspended load than wash load, but more difficult to measure bed

load than the bed material load. This is one of the reasons for the overlapping separation used in this report. To put matters in perspective, however, it does seem (from preliminary data: Church et al., 1986) that most of the suspended load at sites presently sampled on the Mackenzie is in fact "wash load". This should not be taken to imply, however, that most of the bed material load is bed load!

3.2 SUSPENDED SEDIMENT ISSUES

The issues that involve suspended sediment relate not only to the quantities of sediment being moved at different places in the Mackenzie system and at different times; they refer also to the character of that sediment too. In particular, much of the nutrient material in a river, and much of the contaminant loading, is actually bound to the fine particles that move in suspension. The following five major issues relating to suspended sediment movement are discussed in Part Two:

1. The magnitude, timing and spatial pattern of inputs of suspended sediment from the Mackenzie and Peel rivers to the Beaufort Sea. In any attempt to understand the behaviour of the offshore sediment plume (thought to be very important in terms of the effect of turbidity on marine productivity and in relation to the transport of spilled oil), this information is vital. Its importance in the context of rates of infill of pipeline trenches, and instability of accumulations of loose sediment on the sea bed, is also obvious.

2. The magnitude of inputs of suspended sediment to the Mackenzie Delta. In view of likely global warming in the next century, the possibility of rising local sea levels and thaw of permafrost in the Delta lead to obvious concerns regarding the very existence of the Mackenzie Delta. (The concerns are not only environmental: proposals already exist to bring oil and gas from offshore via pipelines across Richards Island, with routes that involve areas of low-lying land.) A major variable in the continued existence of the Delta is clearly the rate of input of suspended sediment over the Delta surface in relation to rates of submergence.

3. Supply of nutrients to the Delta and Beaufort Sea. The biological productivity of both the Delta and the Sea is determined, to a great extent, by the availability of nutrients. Much of that nutrient supply is transported into these areas by the Mackenzie, bound to fine sediment. Any development of the catchment area that interferes with this process (e.g. the damming of a major tributary for hydro power production and the trapping of sediment in the associated reservoir) will have repercussions on the productivity of those two areas. In this regard, therefore, data are needed now on the magnitude, timing and spatial pattern of nutrient supply to those areas.

4. Transport of contaminants bound to the suspended load. Issues relating to contaminants in the Mackenzie River have already arisen since Berger made his comments in 1977: one in particular is the detereoration in fish quality in local areas, which some believe is related to hydrocarbon intake. Whether this association is real, and, if so, whether it is natural (from oil seeps) or artificial (from refinery effluent), is not known. Nonetheless, it highlights the need to determine natural levels of contaminants, now, so that the impacts of future development can be more accurately assessed.

5. Identification of the sources of suspended sediment in the Mackenzie River. Determination of sediment, nutrient and contaminant loads at the entrance to the Delta and at the margins of the Beaufort Sea will help address the issues noted above; but, clearly, this information, on its own, is of limited use. A quantitative breakdown of where, within the Mackenzie system, these sediment, nutrient and contaminant loads originate is also needed. Only in this way, can the impacts in one subbasin, e.g. the Liard, be accurately assessed.

3.3 BED MATERIAL ISSUES

The issues related to bed material, and its movement, in the Mackenzie are somewhat different. Nutrients and contaminants are generally bound to fine-grained sediments, and in most places the alluvial bed of the Mackenzie appears to be dominated by sand, with extensive areas of gravel in steeper reaches, though there is some silt in slow-flowing parts. Clay deposits do occur, but appear to be primarily older sediments laid down in post-glacial lake bodies, as noted in Section 2.

The coarse granular bed material load of the Mackenzie is of interest to many agencies, primarily because of its more limited mobility compared to the suspended load: it tends to accumulate in slower areas of the river, thereby causing problems or creating resources, depending on the circumstances. Six such issues are discussed in Part Two:

6. Transport of bed material along Mackenzie River.

Scour, movement and accumulation of bed material is implicated in many aspects of the river's management: navigation, potential undermining of river structures (including pipeline crossings), ice jamming during spring breakup, extraction of borrow material from the river bed, etc. Before these problems can be considered seriously (Sections 7-11), a knowledge of bed material transport rates, along the river, is needed. Such information is also crucial in assessing the longterm fate of the Delta itself.

7. Shoaling of bed material as an obstacle to navigation.

Movement of freight along the Mackenzie Valley is primarily by barge. Traffic, which is already restricted because of rapids and shoals, will need to be increased to cater to hydrocarbon development in the years ahead. A detailed programme of dredging has already been proposed, but its success, and ongoing cost, is uncertain in many areas because of inability to predict infill rates.

8. Channel scour under ice and breakup conditions.

The Mackenzie River is already crossed by one pipeline (upstream of the Liard confluence) and proposals have been submitted to cross the East Channel of the Delta. A major concern, widely recognized, is the stability of such crossings in the light of bank and bed scour. While all such sites are subjected to careful analysis in this respect, this should not mask the fact that very little is known about river scour processes in ice-covered conditions. Analysis to date, therefore, must be considered questionable.

9. Shoals as controls on the location of ice jams.

Development along the floodplain of the Mackenzie will take place more rapidly in the future. Flooding will, therefore, become a recurrent worry. A major cause of flooding in northern areas, is short-lived ice jamming during spring breakup. In turn, there is clear evidence to indicate that many of the sites of preferred ice jamming on the Mackenzie are related to shoaling of the channel with bed material. More research is needed into this area with the goals of improving predictions of ice jam occurrence and levels, and assessing whether dredging of the bed can be a cost-effective remedial solution.

10. Expansion of artificial islands at Norman Wells.

As part of the Norman Wells Expansion Project in the early 1980's, Esso Resources (Canada) Ltd constructed six artificial islands in the Mackenzie river, on both sides of the main shipping channel. Since that time, these islands have grown by trapping sediment that has been transported from upriver. Various government departments have expressed some concern about this expansion, partly in the context of the effect that it may have on ice jamming in the region.

11. Extraction of bed material from the Mackenzie for use as borrow material. Granular borrow material will be needed in vast quantities in the Mackenzie corridor as development accelerates, especially for pipeline construction. Large areas of the north bank are deficient in granular material, and attention is now being turned to the bed of the Mackenzie as a possible source, especially after the ease of extraction of such material in the Norman Wells expansion project. Largescale extraction of sand

and gravel from the bed will certainly have an impact on the river. This could be beneficial or adverse depending on the location, quantities and duration of extraction. The possibility of directing mining to areas in which shoals are already a hazard to navigation, or where they act as a catalyst in ice jamming, is certainly worth considering.

3.4 SUMMARY

Acquisition of sediment data in the North is expensive. It often cannot be justified on the basis of one agency's interest. And yet, seen from a different perspective, in many cases these sediment related issues touch so many different departments that failure to acquire the data cannot be justified either. The obvious solution is some form of inter-departmental (including private enterprise) cost-sharing. While it is beyond the scope of this report to explore this point in any detail, it is hoped that the text that follows will make it clear why this approach to sediment-research in the Mackenzie basin is necessary.

PART TWO

1. INPUT OF SUSPENDED SEDIMENT TO THE BEAUFORT SEA

The transport of fine sediment, in suspension, by the Mackenzie into the Beaufort Sea (including the Mackenzie estuary) is of interest to numerous agencies for different reasons, not only in terms of the mass of sediment, but also the chemistry of material that is adsorbed on it. The latter is treated below as separate issues. Strictly speaking, the sedimentary environments of the Delta, and inputs to the Beaufort Sea, fall beyond the geographic terms of reference of this contract. They have already been treated by Lewis (1987, in prep.). Nonetheless, it is essential to highlight those studies in the Beaufort Sea that are strongly influenced by sediment inputs from the Mackenzie River.

(a) ISSUES

The Atlantic Geoscience Centre of the Geological Survey of Canada is engaged in a sediment budget for the Beaufort Sea shelf in which the annual input of suspended material by the Mackenzie, at its mouths, is a key component. The budget is an important issue for several reasons. Above all, it provides basic control for estimates of annual sedimentation rates on the shelf which can then be compared with net accumulation rates. Apart from its scientific significance in terms of understanding the evolution of the estuarine evironment, these data are needed in estimating probable rates of infill of pipeline trenches, glory-holes, ice-scours, etc. (Hill, 1987, pers. comm.). In addition, in areas such as the Mackenzie Trough, these processes of scour and fill play an important role in determining seabed stability characteristics (submarine slumping etc.) (Erickson and Fowler, 1987).

The Institute of Ocean Sciences of the Department of Fisheries and Oceans (DFO) is involved in two Beaufort Sea projects that are related to the flux of suspended sediment from the Mackenzie. One is concerned with the input of hydrocarbons; the other deals with the input of nutrients as this relates to primary productivity in the shelf area. Both hydrocarbons and nutrients are moved down the Mackenzie and into the sea primarily as part of fine sediment in suspension. These two topics are dealt with separately below (Sections 3 and 4).

More generally, the Institute is interested in the magnitude, timing, spatial pattern and grain size breakdown of suspended sediment itself introduced to the Beaufort Sea by the Mackenzie. The plume of suspended sediment, for example, affects primary productivity through its control on light transmission into sea water. And, in terms of offshore oil development, the affinity of fine sediment for hydrocarbons suggests that Mackenzie wash load may play a major role in transporting the products of oil spillage in the shelf, i.e. Mackenzie wash load

may act as a partial natural cleanser in relation to chronic offshore oil spills (Macdonald, 1986, pers. comm.).

Personnel at both of these centres also emphasize one further point: the sediment input of the Mackenzie-Peel rivers will always be of major concern to studies of the estuarine area, and it is essential that a long-term record be built up, not merely to establish accurate long-term averages, but also for monitoring annual variances, cycles and long-term trends.

(b) INFORMATION NEEDS

What is needed by both agencies working in the Beaufort Sea is an accurate estimate of the input of suspended sediment by the Mackenzie River, at its distributary mouths, not merely in terms of an annual total, but also broken down by categories.

This breakdown should subdivide the load according to timing (month of the year), by distributary outlet (East Channel, Middle Channel and Reindeer Channel), by particle size, and also, preferably, by physical and chemical composition of the suspended clastic particulates. Even these figures should not be bulk totals. Total load at the mouth of Reindeer Channel, for example, is insufficient: that load should also be broken down according to month of the year, and how the particle size varies with time of the year.

Such refinement is needed if the issues raised above are to be adequately addressed. The spatial pattern of accumulation in the shelf, for example, obviously depends on the relative importance of inputs from the major Delta channels. It also depends, however, on the time of year that each channel is supplying the sediment. At times of severe pack ice conditions in the Beaufort Sea, the Mackenzie sediment plume may be ponded in the nearshore area (Harper and Penland, 1982), while even in ice-free periods, wind direction, which tends to vary seasonally, will affect where the sediment from a given distributary will settle over the shelf.

(c) ADEQUACY OF EXISTING INFORMATION

Bornhold (1975) undertook one of the first studies of suspended sediment from the Mackenzie River in the Beaufort Sea, collecting samples at various heights above the sea bed in August and September of 1975. His work was particularly valuable in its microscopic examination of the physical and mineralogical composition of the particulates in suspension, differentiating between (a) mineral clasts (finer than 5 µm; (b) organic aggregates (100-400 µm in size) of mineral grains; (c) dense red-brown aggregates (40-100 µm in size) of mineral particles; and (d) plankton. He thought that most of the aggregates originated in the river itself or immediately at its entrance to the Sea (bonded by colloidal iron oxide and hydroxides and complexed iron) rather than being the result of fecal pelleting.

Though primarily qualitative, Bornhold's observations are important given the common tendency to treat suspended particulate matter as though it is a dispersion of mineral clasts. Though flocculation is known to be much more pronounced in brackish and marine water, the observations do suggest that more attention should be paid to the physical composition of suspended river water also. For example, a distinction between inorganic and organic (combustible) components of the particulate load would be a useful starting point. D'Anglejan and Smith (1973) have previously advocated the ash content of filter residues as a simple measure of the relative proportions of inorganic and organic constituents in estuarine water, but it does not seem to be widely used on Canadian rivers. The simple distinction between clastic material and organic material (detrital parts of plants and animals as well as small organisms) may be an important one not only as an index of available nutrients, but also in terms of the correlation of the suspended load with concentration of adsorbed material.

Davies (1975) made the first real attempt to compute the magnitude of suspended sediment inputs to the Beaufort Sea from the Mackenzie, by analyzing sediment and discharge data from the Water Survey of Canada WSC) at Middle Channel upstream of Napoiak Channel (listed by Davies as station 10MC006, but corresponding to the geographic coordinates of 10LC008) in 1974-75. Discharge measurements indicated that the channel here accounted for 84% (June 1975) to 94% (January-March, 1975) of the Mackenzie water input, and, by inference, by far the major part of the sediment input. The site, however, is still some distance from the Delta mouths (about 125 km) and settling of sediment between here and the Sea should not be overlooked.

Samples were taken on 8 occasions during July, August and September of 1974, and interpolated to give monthly yields of 44 million tonnes (Mt), 64 Mt and 6 Mt respectively. The three month total of 110 Mt is substantially higher than the annual figure of 15 Mt previously suggested by Lisitzin (1972) and widely quoted at that time: however, loads in August 1974 were abnormally high, as indicated by data from the station above Arctic Red River.

Harper and Penland (1982), in a report on sediment dynamics of the Beaufort Sea for the Atlantic Geoscience Centre, once again emphasized the dearth of data on the suspended load of the Mackenzie and its importance to the Beaufort Sea studies. Based solely on the data from Davies (1975), they regarded sediment inputs from the Mackenzie to the Sea to be more or less uniform in the summer period peaking in August. Subsequent analysis of the records for the Mackenzie above Arctic Red River (station 10LA003, discussed in Section 2) suggests that this is wrong, with peak loads in June and May. This timing may be an important control on the proportions of the 10LA003 load that settle out on the Delta, settle in the immediate nearshore area

and diffuse offshore, bearing in mind the sea ice coverage at this early time of the year.

Analysis of sedimentation rates offshore, based on the accumulation of muds during the Holocene (Meagher, 1978; O'Connor, 1982), led Harper and Penland to estimate long term rates of about 42 million cubic metres per year. This figure is substantially less than that reported by Lewis at that time for the Mackenzie at Arctic Red (about 86 million cubic metres), leading them to suggest that much of the input probably escapes to the continental shelf or the ocean basin. (Although the figure quoted for the Mackenzie load is high - because of the abnormality of the August 1974 loads - it is not excessive as an estimate of the combined loads of the Peel, Arctic Red and Mackenzie Rivers, which is the figure that matters in the present context. Data are provided in Section 2). This conclusiion of Harper and Penland should be regarded as tentative. There are serious problems in the interpretation of the offshore data and there are major gaps in the nearshore areas inside the 10 m depth. Even if the estimates for present day accumulate rates on the shelf are reasonable, an alternative interpretation remains, viz. that a substantial part of the sediment from the Mackenzie settles on the subaerial Delta. This possibility emphasizes the need for separate determination of suspended loads upstream of the Delta (Section 2) and at the Delta mouths.

(d) RECOMMENDATIONS

Comprehensive recommendations for addressing this topic fall beyond the mandate of this report, and have been provided by Lewis (1987) in a planning document concerning the Mackenzie Delta. In the context of the Beaufort Sea, he emphasizes the need for further research on the character, amount, distribution and timing of sediment transport in the Delta distributaries, without detailing specific sites. The complexity of the distributary network, in fact, renders monitoring of the suspended sediment flux to the Beaufort Sea a rather formidable logistical operation. Nonetheless, it is simplified by the dominance of three major channels.

1. Suspended sediment sampling should be undertaken at strategic points on Reindeer Channel, East Channel and Middle Channel for the purpose of determining the combined suspended sediment input to the Beaufort Sea, together with its change through the ice-free season, and the variation in load and particle size during the year between the distributaries.

A period of three years is probably a minimum for assessing the stability of this partition among the three distributaries,

and for determination of the percentage of the sediment inflow to the Delta that actually reaches the Sea. Depending on the results, and on the hydrological character of those years, a longer programme may be needed.

Suitable sites would be those used for discharge measurement by Davies (1975): No. 15 downstream from the entrance of Reindeer Channel; No. 17 on East Channel downstream from Neklek Channel; and a new site on Middle Channel upstream of No. 20, prior to the loss of flows down the unnamed channels gauged by Davies at Sites 18 and 19. This new site could be at Station 106 marked on the Hydrology Information Series 1:250,000 Sheet 107C (Inland Waters Directorate, 1985).

Given the interest in this topic of other agencies already noted, it would seem logical to plan a comprehensive programme with the overheads shared among the relevant parties. This would allow frequent sampling of the suspended sediment, with sufficiently large volumes to permit not merely determination of sediment concentration, but also particle size analysis, and possibly analyses of nutrients and some contaminants. Further discussion of this is deferred until Sections 3 and 4. Shared funding would permit a basic in-field laboratory near all three sites, allowing filtration in the field, and thus reducing the volume of water that would have to be moved to the main laboratories. Large water volumes are, of course, a less serious problem if pump samplers and centrifuging is used (Erickson and Fowler, 1987).

In addition to monitoring stage and water discharge, water temperature should also be measured. Given the strong change from 0° to 16° (or more) Celcius noted by Davies (1975) between May and July, temperature may have a significant effect on the fall velocity of the wash load, and hence partially control sediment concentration.

2. INPUT OF SUSPENDED SEDIMENT TO THE MACKENZIE DELTA

A substantial portion of the sediment input to the Delta (and to the Beaufort Sea) originates from the Peel River, which joins the Mackenzie downstream of Point Separation. The Peel is particularly significant on the west side of the Delta: only about 15% of the water entering the southwest side of Shallow Bay originates from the Mackenzie-Arctic Red (Lewis, in prep.). Strictly speaking, input from the Peel is beyond the original terms of reference, but it will be treated in this study for the sake of completeness.

(a) ISSUES

In addition to the Beaufort Sea sediment budget described in Section 1, the Atlantic Geoscience Centre is also investigating the annual accumulation of sediment on the Delta and, in particular, its spatial pattern. The Delta is at present in a very delicate state of balance in terms of the aerial extent that is not submerged. This balance is controlled by the pattern of sediment input, the direction and rates of sea-level change, the pattern of coastal erosion, and rates of permafrost aggradation or degradation in the Delta.

The above comments may seem somewhat alarmist. As noted by Lewis (in prep.), the traditional view (Johnston and Brown, 1965; Hollingshead et al., 1978) is that the modern Mackenzie Delta has formed by prograding rapidly into an estuarine environment during conditions of relative sea level stability. In fact, recent work on sea level changes (Forbes, 1980; Hill et al., 1985) contradicts this view. Their observations indicate that relative (local) sea level in the Beaufort Sea has been rising ever since 27,000 years BP, apart from a small oscillation between 16,000 and 11,000 years BP. Hill (1987, pers. comm.) puts the rise in the last 10,000 years at between 38 cm and 71 cm per century. The rise is attributed largely to migration of sublithospheric material (previously extruded under the sea floor by crustal loading of the land in the last glaciation) back towards the land mass following deglaciation. Tide data for Tuktoyaktuk have been examined by Forbes (1980) for the period 1952-1975 and show a continuing increase of the order of 4 cm, but, given the large scatter, was not considered statistically significant.

Nonetheless, the realisation that local sea level has been rising throughout the Holocene, coupled with expectations of further increases in the next century because of melting of ice by higher temperatures (the "greenhouse effect"), emphasizes the uncertainty regarding the future. The possibility of further submergence is increased by the likelihood of degradation of permafrost in the Delta as temperature increases.

In this context, therefore, delivery of sediment to the Mackenzie Delta, and trapping by the Delta surface (rather than

throughflow to the Beaufort Sea) is an extremely important issue. Expectations of continued local sea-level increase in the next century lead to expectations of shrinkage in delta area. The pattern of this change will depend not only on present delta topography, but also on the pattern of present rates of aggradation on the subaerial and submerged parts of the delta. At present there is a wide range of opinion as to the proportion of the Mackenzie-Peel sediment input that is trapped on the Delta.

The possible impact on these processes of damming of the Liard for hydroelectric power generation is also an issue. It has been addressed by Lewis (in prep.), and is discussed to some extent in Section 5 in connection with sediment yields from the Liard basin.

(b) INFORMATION NEEDS

Discussion of the data required for mapping the spatial pattern of sedimentation on the Delta is provided by Lewis (1987; in prep.). Here attention is focussed on the requirements for the more simple, but still vital, task of determining the gross sediment accumulation on the Delta surface.

Provided that measures are taken to determine output rates to the Beafort Sea (Recommendation 1), this can be conveniently done by comparison of these outputs with the inputs of the Mackenzie upstream of Arctic Red River, the Arctic Red itself and the Peel River. Contributions from other channels west of the Delta is assumed insignificant based on their small annual runoff volumes.

(c) ADEQUACY OF EXISTING INFORMATION

Summary of data

Most of the data pertinent to this problem refer to point estimates of sedimentation on the Delta surface, much of the work being initiated by BC Hydro in an attempt to evaluate impacts of possible damming of the Liard on the sediment budget of the Delta. Reference may be made to the reports by Hardy Associates (1982) and Cordes & Associates (1984), with a general synthesis of the data and literature provided by Blachut et al. (1985). Considerable material has also been assembled by Applied Ecology Consultants (1987). The National Hydrology Research Institute is currently investigating the sedimentation regime of lakes in the Mackenzie Delta (Marsh, 1987, pers. comm.). A major problem with these data, however, as recognized by most of the authors, is the difficulty of extrapolating to the whole Delta surface from spot samples. Sedimentation rates in lakes, for example, varied between 0.3 mm/yr to 10 mm/yr, depending on lake type, elevation, proximity to distributary channels, location in the Delta, etc. In view of this variance, the logical starting point is with the

sediment input records of the Mackenzie, Arctic Red and Peel Rivers.

Lewis (in prep.) has prepared the first comprehensive analysis of these yields based on WSC data for the Mackenzie upstream of Arctic Red (10LA003), the Arctic Red near its mouth (10LA002) and the Peel River above Fort McPherson (10MC002). The data refer to the years 1972-1983. The method of computing yields was by the establishment of a sediment rating regression equation linking the logarithm of suspended sediment concentration (daily mean value) to the logarithm of discharge (daily mean value).

The regressions were based on 206 sampling times for 10LA003, 56 times for 10LA002 and 77 times for 10MC002. Because logarithmic regressions of this type lead to bias in the prediction of the actual (non-logarithmic) values of concentration (Ferguson, 1986), the appropriate correction was applied to scale up the predictions. The adjusted equation was then used, in each of the three cases, to predict the sediment concentration (for each day of record) in the period from the daily mean discharge for that day. The sediment yield for each day was then determined from the product of daily mean discharge and the predicted concentration. These values were then summed to give yields for each month. The resultant mean values for each month in the period of record are given in Table 1. The data indicate a total input to the Delta of the order of 126 Mt per year, of which 70% is from the Mackenzie itself, and, interestingly in the light of previous assumptions, 62% occurs in the months of May and June.

Determination of sediment loads: methodological concerns

The use of the sediment rating curve approach to estimate concentration is a significant departure from the normal procedure used by the Water Survey of Canada to compute sediment yields. In the latter case, the actual concentration measured on a particular day is used, and values for unsampled days are interpolated, essentially by eye. The procedure is as follows. The cross-sectional mean concentration value at times of sampling are plotted on a copy of the stage recorder chart at the time of day of sampling. A "sediment concentration hydrograph" is then constructed by drawing a smooth curve through the concentration points on the recorder chart copy. "The water level record on the recorder chart, daily precipitation data, water and air temperatures, turbidity readings, sediment rating curves, or other environmental factors which may be known, should be used as a guide in restoring the concentration hydrograph" (Water Resources Branch, 1983, p. 30). The daily mean concentration for each day is then determined from this restored sediment concentration hydrograph, and multiplied by daily mean discharge to give the suspended sediment load for the day.

The standard WSC method is therefore quite subjective (though objectivity does not necessarily guarantee more accurate results). What is also significant, though, is that, because the period between samplings can be quite long (days or weeks), one erratic sampling value can bias the yields throughout the adjacent time period. An indication of this is presented below and should emphasize why the rating approach (provided that it is based on a strong correlation) is probably superior.

The example refers to station 10LA003 for the month of August 1974, a time of very heavy sediment loads. The total suspended sediment load computed using the WSC approach is 117.7 Mt, based on three sampling days. Prediction of the August total using the BC Hydro rating curve (based on 1973-74 data) gave a value of only 44.7 Mt! The huge difference arises because one of the three August samplings showed a huge sediment concentration: 9640 mg/L, more than three times greater than the next highest on record at this site! The rating curve prediction corresponds far more closely with estimates of the August 1974 load downstream (on the Middle Delta channel: WSC Station 10LC008) of 63.9 Mt (based on the WSC approach and three samplings). Though WSC itself is obviously well aware of the limitations of monthly totals based on such small samples, this is clearly not always the case with users of WSC data. The August 1974 load, and the inferred sediment concentration hydrograph for the month, have featured prominently in many reports on the Mackenzie.

It would be instructive to compare actual monthly yields of individual years, using the rating curve approach, with those previously published by WSC based on its operating procedure. As noted, the Water Resources Branch is aware of these problems, and is now reviewing use of the sediment rating approach for computing yields (Cashman, 1987, pers. comm.)

The sediment rating approach is, however, only a first step in a better prediction of sediment concentrations, because suspended sediment is not uniquely controlled by water discharge. Other factors are important. Many of these are routinely measured, and there is no reason why multiple regression equations should not be used for predicting concentration. Their accuracy is likely to be much greater. Much of the suspended load is "wash load" from valley slopes and channel banks rather than the river bed itself. A key factor controlling concentrations therefore must be sediment availability: this may be expected to become depleted during the ice-free season. Another factor will be the actual mechanism of sediment production: these are not the same in summer rainstorms and spring snowmelt. Stratifying the sample data by month may therefore improve predictions. Differences in concentration at the same discharge, according to position on the hydrograph, would be expected to improve the regression. Rate of change of stage affects bank scour rates (Carson et al., 1973) and is worth including as a predictor. Temperature of the stream water is also likely to important as already noted.

Finally, it should be recognized that irrespective of the procedure used for estimating daily mean concentration values, additional investigation has to be made of the accuracy of the cross-sectional mean values at the times that samplings are taken. In most cases only one vertical is sampled at a cross-section, and then the value is adjusted to represent the whole section. There is nothing inherently wrong with this strategy, but, obviously, it is important to determine the errors associated with it (discussed below for 10LA003).

Determining sediment loads: data quantity and quality

With the limitations of these various procedures now noted, it remains to assess how serious they are in the context of the three stations under discussion. The limited scope of this review prevents this from being done in detail, but certain points do need to be emphasized.

The sampling programmes for the three Delta input stations are summarized in Tables 2, 3 and 4. In the case of the Mackenzie it can be seen that considerably more data have been gathered since 1983, and need to be included in any statistical analysis. The distribution by year up to 1983 shows a strong concentration in the 1980-83 period which may not be representative of the long term pattern The June-August (inclusive) totals for these years, for example, range 29.5 to 49.8 Mt (as computed by WSC). These may be at the low end of the year-to-year distribution: the mean 1972-83 total for those three months according to Lewis's data is 62.9 Mt. (At the same time, it should be noted that peak flows in the 1972-1983 period were somewhat higher than during the previous thirty years, based on discharge data from Norman Wells (Church et al., 1986, Fig. 4.8)). In addition, the virtual absence of samples in May, comparable with July as the second biggest month, must be considered a major worry. Notwithstanding the logistical difficulties of sampling during breakup, this absence of data must be adressed. The limited data set for Arctic Red River (Table 3) is not too serious given the small yields. Again, however, the absence of data during breakup is a concern. The bias of data for the Peel (Table 4) to July-September must be regarded as a major problem given the apparent dominance of May and June in terms of actual sediment transport using the sediment rating approach.

The strength of the sediment rating regression itself is fairly good for the Mackenzie (prediction of sample variance equal to 63%), even better for the Arctic Red, but poor for the Peel (35%). Actual prediction of transport rates (the product of Qc) is of course better because of the inclusion of discharge on both sides of the equation. Mathematically, it can be argued that the improved correlation between transport rate (Qc) and discharge (Q) - compared to c against Q - is spurious, but this itself is a misleading point. If the purpose of the analysis is

the prediction of loads, then what matters is the strength of regressions in which load (Qc), and not concentration (c), is the "dependent" variable.

Given the high sediment fluxes of the Peel River, its poor sediment rating relationship is especially unfortunate, and the reasons for this need to be determined. Equally important - and even with a good rating - there must exist some concern about the accuracy in computing loads on the Peel, bearing in mind the apparent dominance of May and June in the sediment flux (Table 1). There may well exist backwater effects from the Delta (Wedel, 1988, pers. comm.). If this is the case, then water stage in this early period will overestimate discharge, which will in turn lead to overestimation of loads, irrespective of the method used in their calculation. The same concern exists for the other two stations, but it is greatest for the Peel: 45% of its suspended load is computed as occurring in May (Table 1), compared to only 28% for the Arctic Red and 20% for the Mackenzie. (See also the comparison of May loads on the Liard and the Mackenzie discussed in Section 5).

Details of the sampling locations for these three sites have not been examined. It should be borne in mind, however, that at all three sites, cross-sectional mean concentration is primarily based on a sample at a single vertical (K sample). WSC policy is to supplement single-vertical sampling days with occasional replicate (R) samplings in which five verticals in the cross-section are used. Comparison of the R concentration value with the K concentration value during a given sampling session then provides a k-coeffficient which is used to adjust other concentrations in that week, month, etc. that have been determined from only the one vertical. Unfortunately, because of limitation of resources, R sampling is undertaken at 10LA003 only once a year! Apart from variability in k from year to year, (which can be examined), there is the problem of variability in k within a year, something for which no data appear to exist. This is serious because there are reasons for suspecting that k will vary with stage. Sampling at the single vertical at this site (but not the R sampling) is restricted to the top 4.5 m of the water column. The concentration in the sample, relative to the concentration in the full vertical, would therefore be expected to vary with stage: at lower stages, sampling extends closer to the bed (where concentrations are higher) than at high flows. This may explain why the sand fraction (greatest in the lower part of the water column) shows a decrease at high discharges. Data regarding the k coefficient have not been examined for the other two sites.

A further point to be considered is that even where sampling is undertaken throughout the full length of the vertical, the dimensions of the sampler prevent collection of suspended load from very close to the bed. This is the so called "unsampled" suspended sediment (Colby, 1957). In some cases, especially sand bed rivers, it can amount to a substantial amount of the full

suspended load. Colby (1957) has suggested ways of estimating this component. Loads currently computed at sites in the Mackenzie basin do not appear to include this fraction.

(d) RECOMMENDATIONS

Mackenzie River above Arctic Red River.

Lewis (1987) emphasizes the need to continue monitoring suspended sediment concentrations at Station 10LA003 (Mackenzie River above Arctic Red River). This is certainly essential if other work on the Delta, such as monitoring of sediment output to the Beaufort Sea, is undertaken. However, in the longer term, routine sampling at 10LA003 may not be needed. The important point is that a good sediment rating relationship has now been obtained for this site. Instead of continuing routine sampling at 10LA003, future loads can be predicted using this relationship, especially if improvement in the precision of prediction can be made by inclusion of other variables. This would allow redeployment of resources elsewhere.

One cautionary note is in order though. The good correlation that exists between suspended load and water discharge, on a daily basis, at this site merely means that the precision of predictions using this approach is good. We have no assurance about any possible bias that might exist in the data. Reasons for concern in this respect have already been given in the very brief overview above. A more thorough review of the reliability of the sediment data at this station appears essential.

> 2.1. A full sediment station review be undertaken for Station 10LA003. Particular attention should be focussed on the stability of the k factor. This will necessitate a detailed sampling season to assess the variability of k.

The review should also examine means of improving the sediment rating curve predictions by stratifying the data, e.g. separation according to month of the year, position on the hydrograph, etc., and inclusion of other variables, e.g. rate of change of discharge. Some thought will also have to be given to the errors associated with lack of data in the early stages of spring breakup. Finally, attempts should be made to develop predictive equations for concentration by size class, and not merely by total suspended sediment.

The need to verify the accuracy of the existing data for this site is now more important than continuation of the present sampling programme. Ultimately only spot samplings, e.g. once or twice a year, will be needed to indicate any shift in the rating relationship.

Arctic Red River near the mouth.

The sediment rating relationship for this site (10LA002) appears to be slightly better than that at 10LA003. On the other hand the Arctic Red River supplied less than 6% of the 126 million tonnes (Mt) per year total input of suspended sediment to the Delta during 1974-83 (Lewis, in prep.). Given this, it would seem that long-term continuation of sampling at this site is not warranted, though it should be undertaken during any period of detailed sediment work on the Delta as outlined in Section 1. The more important task is to undertake a statistical analysis of the existing data to see if the sediment rating predictions can be improved by stratification of data and by inclusion of other variables.

2.2. A sediment station review be undertaken for Station 10LA002, along the lines of that for 10LA003, with the goal of improving accuracy of predictions. Though additional samplings may be needed, especially given the absence of any data since 1975 and during breakup, routine sampling will hopefully not be necessary in the future.

Peel River above Fort McPherson.

Based on present data (Lewis, in prep.), the Peel River accounts for almost 25% of the total suspended load entering the Delta, slightly more than a third of the Mackenzie River input at 10LA003. Its importance is thus much greater than that of Arctic Red River, and it is therefore especially unfortunate that its sediment rating relationship is so poor. A major effort must be made to determine the cause of this problem, and to rectify it if possible. If that cannot be done, it may prevent the use of a sediment rating approach at this station and necessitate long-term routine sampling.

2.3. A comprehensive sediment station review be undertaken for Station 10MC002, following the pattern of 10LA003, especially with a view to using multiple regression procedures in order to assess if predictions of concentration can be improved sufficiently to warrant eventual abandonment of the sampling programme on a routine basis.

General comment

Discussion regarding the adequacy of existing data focussed on the quantity and quality of sediment concentrations, with limited reference to particle size. Throughout, it assumed that data for water discharge were reliable. There are some reasons for questioning whether this assumption is really justified, particularly in light of possible backwater effects early in the summer period, when loads are high.

2.4 A review should be made of the quality of the discharge rating curves at these three sites during the early summer period, and, if found unsatisfactory, improvements should be attempted, e.g., by monitoring water slope as well as stage.

These recommendations refer to items directly within the terms of reference of the present study. Together with those in Section 1, they will enable determination of gross sediment accumulation within the Delta, information that simply does not exist at the present time. Other aspects of sedimentation within the Delta are addressed by Lewis (1987).

3. TRANSPORT OF NUTRIENTS IN THE SUSPENDED LOAD

(a) ISSUES

Inputs of nutrients to the Delta and to the Beaufort Sea are of concern to many parties, since they exert a major effect on the biological productivity of both areas. Nutrient movement in the Mackenzie River is related to sediment transport because most of the nutrient load is thought to be adsorbed to fine sediment.

Nutrient availability is not an "issue" as such, at present, but information regarding the amounts, type and timing of nutrient supply by the Mackenzie is crucial to understanding the pattern of primary productivity in the Beaufort Sea, and how it might be disturbed by offshore oil exploration. It is a topic of some interest to the Institute of Ocean Sciences: the timing of nutrient input to the Sea, for example, is of critical importance in understanding the growth of Arctic marine biomass. Moreover, given that contributions from different parts of the Mackenzie basin apparently peak in different months of the year (refer to previous observations on the Arctic Red, Peel and lower Mackenzie in Section 2, and to upstream tributaries in Section 5) changing inputs over time are, to some extent, related to geographic changes in inputs.

The input of sediment-bound nutrients to ecosystems in the Delta is also of interest to various agencies, including BC Hydro in connection with proposals to dam the Liard River for hydro-electric power. Again, timing is extremely important, given that widespread inputs to the Delta surface depend on overbank flooding, primarily during the spring breakup. Input to lakes in the Delta is more variable depending upon how well-integrated the lake is with the distributary network.

(b) INFORMATION NEEDS

The prime information requirements regarding nutrients are:

i. the annual load at the entrance to the Delta and at the mouths of distributaries at the Delta seaward margin, both in total, and subdivided according to particulate and dissolved components;

ii. the breakdown of these loads according to the time of year;

iii. the origins of these nutrient inputs within the Mackenzie basin.

The primary nutrients of concern are organic carbon, nitrogen and phosphorus. Attention must be given, however, to methods of analysis to ensure that, as far as possible, the most meaningful measures of bioavailable nutrient (i.e. nutrients in a form readily available for incorporation in the biomass) are

determined. The Mackenzie River Basin Committee (MRBC) (1985), for example, noted that a large portion of the nutrient data summarized in its study referred to forms not available for biological uptake. This conclusion was inferred from the poor correspondence spatially, within the entire basin, between nutrient levels and biological productivity. Other factors, of course, do affect productivity, especially oxygen concentrations and ambient temperatures, as well as temporal changes in all these variables.

(c) ADEQUACY OF EXISTING INFORMATION

The Mackenzie River Basin Committee (1985) has summarized information on nutrients based on data files in a report by the Water Quality Branch (1981) of Inland Waters Directorate. Data availability for the mainstem Mackenzie is summarized in Table 5. No details of the breakdown by timing or river discharge are available in the 1985 interpretative report, but the generally limited and patchy data assemblage would seem to be inadequate to answer the questions raised above.

In terms of organic carbon, the MRBC report does note that both dissolved (DOC) and particulate (POC) components peak in the summer months throughout the broader Mackenzie basin. On the Mackenzie at Norman Wells, peak summer values for total organic carbon were about 15 mg/L. The particulate component (suspended flora and fauna, and fragmental and decaying organic material) accounted for about 50-60% of TOC in the basin as a whole during May and June decreasing to less than 30% in the winter months. Ericksen and Fowler (1987) reported very low POC values in Delta channels in April 85 and February 86, of the order of 0.1-0.4 mg/L. This is hardly surprising given the low concentration of suspended sediment at this time of the year.

MRBC (1985) partitions total nitrogen into particulate and dissolved components, with the dissolved portion further subdivided into organic nitrogen (humic compounds and other products of decomposition), ammonia and ammonium and the nitrite and nitrate anions. (Table 5 combines the dissolved organic nitrogen and dissolved ammonia and ammonium ions as Total Kjeldahl nitrogen). Bremner (1965) noted that, in general, 20-40% of the total nitrogen in most surface soils is in the form of bound organic material (amino acids). Detailed comments on seasonal change in nitrogen speciation were presented only for the Athabaska River: total concentrations of nitrogen did not change markedly through the year, but, as might be expected, the percentage in particulate form increased during summer high flows. In April and May, particulate nitrogen amounted to 0.35 mg/L, representing about two-thirds of the total load.

Total phosphorus concentrations were also subdivided by MRBC into both dissolved and particulate forms, both of them including inorganic and organic species. In the Athabaska River, particulate forms dominated the total concentrations during April

to August. The only reference to the Mackenzie indicated little change in phosphorus speciation between December and August at Norman Wells, but with only three observations for dissolved phosphorus this is perhaps suspect. Particulate phosphorus accounted for 82% of the average total phosphorus at Norman Wells and 95% at Wrigley.

Brunskill et al. (1975a,b) and Campbell et al. (1975) made estimates of the fluxes of carbon, nitrogen and phosphorous during the 1971-73 period. Discharges in these years seem to be representative of the post-1970 period. Their data indicate total fluxes to the Delta (from the Mackenzie, Arctic Red and Peel rivers) of these three elements in particulate form amounting to 3.12, 0.13 and 0.05 Mt, respectively, per year. The particulate component accounted for 60% of the total nitrogen input and 88% of the total phosphorous flux. Approximately 92% of the total N and P loads, combined for the Mackenzie (Norman Wells data only), Peel and Arctic Red rivers, originated in the Mackenzie.

The figures above are derived from a very small data base. They were also computed from the sum of monthly means which, in turn, were derived from the product of mean discharge and mean concentration for each month. Brunskill (1988, pers. comm) states that the mean concentration values were "discharge-weighted", rather than simple means; the latter would have led to bias, probably underestimating the monthly loads (Church, 1978; Ferguson, 1987).

Given the limited data, an alternative approach would be to utilize the logarithmic relationship between concentration and discharge, applied to the flow duration data, to estimate annual nutrient loads. Unfortunately, the relationships obtained are not particularly strong: coefficients of determination generally averaged only 50 percent. On the other hand, this may be partly due to the limited variance in discharge sampled. Moreover, the correlation of instantaneous load (rather than concentration) with discharge would be stronger.

In any case the data presently available are inadequate for many of the purposes required, especially in the context of <u>timing</u> of the fluxes and the <u>spatial</u> nature of the inputs from the Delta distributaries to the Beaufort Sea. These issues are just as crucial in terms of biological productivity as annual loads.

(d) RECOMMENDATIONS

3.1. The detailed sediment sampling programme at Station 10LA003 on the Mackenzie upstream of Arctic Red River, recommended previously (2.1), should include sampling of sufficient water to allow additional analyses of nutrients.

Emphasis should be directed to establishing relationships between nutrient concentrations and particular sediment concentrations (e.g. clay concentration or amount of sediment lost on ignition (see Section 1)) and on changes throughout the course of the year, including the ice season. (It should be borne in mind that primary productivity in the Mackenzie Estuary is thought by some to be highest before and during ice break-up).

3.2 Similar sampling should be undertaken at outflow sites from the Delta as part of the sediment sampling programme outlined in Recommendation 1.

By combining this nutrient programme with the direct sampling programme outlined in Sections 1 and 2, overheads will be reduced, and other agencies, such as the Dept. of Fisheries and Oceans, might be expected to contribute to funding.

One warning must be introduced here. Attention should be directed very closely to conditions of storage and mode of nutrient analysis. Normal IWL procedures for the former may be adequate or may have to be modified in consultation with other interested parties. It is assumed that nutrient analysis would be done by DFO, at the same time as their analyses of Beaufort Sea samples, though other organizations concerned with nutrient inputs to the Delta may be interested. What is extremely important is that the same methods are used on the river samples as on the sea water samples. This is essential if the river data are to be used to interpret the Beaufort Sea data.

One of the conclusions to emerge from the literature is that data interpretations are hampered by the fact that different parties use different sampling procedures, modes of storage, and methods of analysis. Coordination is essential to minimize duplication of effort and ensure consistency of data.

It is beyond the mandate of this report to specify methods of chemical analysis. It is sufficient here to point out that previous work has not always clearly differentiated between

nutrients that exist in "available" form and those that are not available for biological uptake. MRBC (1985) notes "nutrients entering Great Bear Lake, for example, are largely associated with mineral material; they are therefore not immediately available for biological uptake and are not likely to be transformed to an available form upon deposition and incorporation into bottom sediments." In emphasizing the dominance of particulate forms of nitrogen and phosphorous in the total concentrations, this point must therefore be borne in mind. While the timing and siting of nutrient sampling must be expanded, it is equally important that analyses focus on the bioavailable components.

4. TRANSPORT OF CONTAMINANTS IN THE SUSPENDED LOAD

The Mackenzie River is generally regarded as a pollution-free waterway. The Mackenzie River Basin Committee (1985) noted, for example, that concentrations of metals in the basin are at natural levels, and organic parameter data are almost entirely below detection levels. Nonetheless, a great deal of interest exists in the transport of both hydrocarbons and heavy metals by the Mackenzie River: and in both cases much of the contaminant is associated with the suspended load. These topics form the first two parts of Section 4.

In addition, recent investigations by Lockhart et al. (1987) indicate that pollution of the river already exists in some forms: they noted widespread contamination of fish with low levels of several organochlorine compounds. To what extent this pollution is related to sediment, and to what extent it is related to specific sources in the Mackenzie basin (as distinct from being part of a ubiquitous contamination of northern watersheds), are not known. This topic is addressed in Part 4.3 below.

4.1. TRANSPORT OF HYDROCARBONS

(a) ISSUES

The transportation of hydrocarbons in the Mackenzie River is of interest to many scientific agencies working in the area. It is of special interest to the Institute of Ocean Science (IOS) of the Department of Fisheries & Oceans (DFO) as it affects the Beaufort Sea. Staff there are currently studying present day movement of hydrocarbons into and through the shelf area in the belief that, by understanding these processes, they will be better able to predict the fate of spilled hydrocarbon material following oil development on the shelf. Information regarding inputs from the Mackenzie, the largest single source, is therefore vital. The topic is also important to many other agencies concerned with aquatic life in the Mackenzie Delta, and in the river itself, e.g. the Northern Environment Directorate of Indian and Northern Affairs Canada (INAC), the Water Quality Branch of Inland Waters, the Freshwater Institute (DFO) and the Environmental Protection Section of Environment Canada.

This interest arises not necessarily because hydrocarbons are regarded as a major contaminant of the river system at the present time, but rather because of fears that levels will increase in the future because of further development of oil and gas in the region, and because of the resultant increase in effluent and chronic spillage. Most oil production in the Mackenzie basin presently occurs upstream of Great Slave Lake, in the basins of the Athabasca and Hay rivers. Smaller amounts are tapped at Norman Wells on the mainstem Mackenzie, and crude oil is shipped from there by the new IPL oil pipeline to Zama Lake in

Alberta; volumes are expected to increase now that this line has been completed (Owens Environmental Services Ltd, 1986). Oil production is expected from the Mackenzie Delta by 1996 and gas by 2000 (Acres, 1987), with pipelines to be constructed along the Mackenzie Valley to Zama Lake. Recently-initiated seismic and exploratory drilling in the Colville Lake area north east of Fort Good Hope affects the Anderson basin rather than the Mackenzie basin directly.

Monitoring of hydrocarbon levels in the hydrologic system now is essential in order to be able to identify how much contamination in the future stems from economic development of the region, and how much is natural. Without such information this will be difficult, if not impossible, to assess. Examples exist in other northern areas of Canada where the failure to obtain background levels of pollutants in the environment has led to inability to separate man-induced from natural contamination, e.g. mercury contamination of fish in the James Bay rivers of Nouveau Quebec. The timetable of development in the Mackenzie basin indicates that these background data are needed as soon as possible.

(b) INFORMATION NEEDS

Information is required in three geographic areas: the mainstem itself, the Delta, and contributions to the Beaufort Sea.

The first requires sampling stations at strategic sites along the Mackenzie River. This is necessary in order to (a) identify parts of the main stem which act as sources for hydrocarbons; (b) indicate the effects of tributaries in augmenting or diluting the mainstem load; and (c) assess the rate of natural elimination of hydrocarbons as they move downstream to the Beaufort Sea.

The spatial pattern of accumulation within the Delta falls beyond the domain of this study. However, prior to embarking on that aspect of the problem, it would seem desirable to obtain gross estimates of accumulation within the Delta as a whole, by comparison of inputs (at Point Separation) with outputs at the mouths of the Delta distributaries. Information from the latter would also furnish, directly, the pattern and magnitude of input to the Beaufort Sea.

Given the dominance of the ice-free season in the transport of suspended sediment along the Mackenzie (Table 1), it would seem sensible to concentrate efforts on that period of the year. On the other hand, the relative importance of free hydrocarbons and those adsorbed to suspended sediment needs to be established throughout the year, and, for this reason, some data are needed during the winter season.

It is also clearly important that the same hydrocarbons and the same sampling, storage and analytical methods are used at all

points within the Mackenzie system. In addition, data are needed for individual species and not simply in the form of total values for particular groups of hydrocarbons. Many species are abundant in the natural environment; others are more clearly the product of oil operations.

(c) ADEQUACY OF EXISTING INFORMATION

Summary of previous work

The earliest comprehensive study of organic material in the Mackenzie basin appears to be that of Peake et al. (1972). More recently, the Water Quality Branch (WQB) of IWL at Yellowknife and the National Water Research Institute (NWRI) at Burlington have collaborated on a study of hydrocarbon movement along the mainstem Mackenzie, sponsored by NOGAP. The goals of that study were: (a) to define the pre-development state of the river and permit identification, if any, of northern hydrocarbon development on the natural aquatic environment; (b) to identify differences between natural contaminants and industrial contributions; (c) to ascertain how hydrocarbons move along river courses, including differences between open-water and ice-covered conditions. E.V.S. Consultants (1985) have undertaken an assessment of freshwater impacts from the Norman Wells oilfield development, with particular reference to the organic components of the oil refinery effluent and cooling water. Hrudey & Associates (1988) have provided a summary of these and related studies, primarily in the context of contamination of fish (See Section 4.3). Additional NOGAP-sponsored work is being undertaken by the Institute of Ocean Sciences in the Beaufort Sea, but no results are yet available.

The work of Peake et al. (1972) was very much a reconnaissance study with sampling restricted to the summer of 1969 at six sites in the greater Mackenzie basin, only one of which was on the mainstem downstream of Great Slave Lake (and one in the Delta at Inuvik). Their analyses dealt mostly with amino acids, chlorins and normal alkanes, and not with the polycyclic aromatic hydrocarbons (PAH's) which are of most concern in terms of toxicity in the food chain. Nonetheless some of their findings are of interest. The n-alkanes were generally below the detection level of 250 ng/l in water, but those in the suspended load ranged 1000 to 9400 ng/g of sediment for individual alkanes. They concluded that the origin of the organic substances apparently lies solely in the soil environment from which the drainage occurred. This view was supported by the fact that the distribution pattern of the amino acids detected in the suspended matter is very similar to that reported by Sowden and Ivarson (1966) in hydrolysates of a brown forest soil and a podsol. As expected, highest adsorbtion of both hydrocarbons and chlorins was in fine sediments.

Somewhat similar conclusions were reached by Nagy et al. (1986, 1987) in reporting the findings of the WQB-NWRI work along

the main stem. The first of these studies deals with low-water conditions in the late summer of 1985; the second with spring runoff in 1986. The latter report concluded that

> "The concentration distributions along the river suggested diffuse inputs of these organics by the spring runoff from the river's drainage basin, which overwhelmed any inputs from the refinery or from the oil seeps."

Nonetheless, the WQB-NWRI studies do show fairly systematic patterns in the two field seasons. (Samples in this investigation were pumped from a depth of about 0.3 m into a continuous flow centrifuge system over periods between 2.5 and 9 hours, depending on turbidity.)

Hydrocarbon concentrations in suspended sediment

The downstream change along the Mackenzie in the concentration of total n-alkanes (C12 to C26) and 16 priority pollutant PAH's in total in sediment centrifuged from the suspended load are shown in Fig. 5, in ng of hydrocarbon per gm of dry sediment. In all cases, concentrations decrease from a high at Martin Island (upstream from Liard mouth), representing the outflow from Great Slave Lake, with a secondary peak in the Norman Wells area (not sampled in 1986) and a smaller hump near the mouth of Arctic Red River. The peak in the n-alkanes at Norman Wells straddles the refinery outflow, one sample being taken upstream (a control site well away from conspicuous natural seepages) and one downstream of it (Tisdale, 1986).

The total concentrations of n-alkanes in the suspended load are higher in the 1985 sample, as might be expected, given that load of suspended sediment (as indicated by turbidity: Table 6) were much higher in the 1986 spring runoff: much of this load would be expected to be coarser sediment (fine sand), lacking adsorbed material. This, apparently, was also true of the 1985 specimen from the Liard (Tisdale, 1986), which would account for its low alkane content and the dilution of alkanes in the suspended sediment of the Mackenzie at Wrigley. (It may also be significant that the centrifuged residue at both sites downstream of Norman Wells in 1985 contained black organic material which appeared to be plant fragments (Tisdale, 1986)).

The concentration of individual PAH's was generally below the detection level of 5 ng/gm in 1985, except on the Liard (which has several gas producing fields in its basin) and at Norman Wells. In fact - and in marked contrast to the alkanes- totals at all station were much lower than those of 1986, and, for this reason, cannot be shown in Fig 5. Why this difference exists between PAH's and alkanes in terms of their importance in the two seasons has not been indicated. PAH's, being generally the product of industrial processes, are usually found on airborne particulates, and deposited on the surface by

precipitation. The dominance of snowmelt in the 1986 sample may account for the higher concentrations of PAH's in the river compared to the 1985 late summer period.

On the Liard River, however, samples were taken of bed sediment in the fall of 1986, and these showed total alkane concentrations of 702-6176 ng/gm and 16-total PAH concentrations of 333-1254 ng/gm. These are about five times higher than the 1986 concentrations in the suspended sediment (Table 6), and seem to indicate that, on the Liard at least, much of the PAH sediment load, as well as the alkane sediment load, could be derived from the bed (though the original source remains conjecture). No data were available however on the grain size of these bed sediment specimens. Comparison with the overall grain size of the Liard bed material (and thus determination of the general availability of PAH's in Liard bed sediment), and with that of the Liard suspended load, is therefore not possible. Determination of concentrations of individual PAH's showed a much broader range of detectable compounds in the bed sediment than in the suspended load, but naphthalene and benzo(k)fluoranthene (the major constituents of the suspended load at all stations) were the dominant constituents of the PAH's in the Liard bed sediment. Phenanthrene and benso(ghi)perylene, the other significant bed PAH's on the Liard, were, however, insufficiently abundant in the suspended sediment samples at all sites to allow quantitive analysis. The relationship between PAH's in bed sediments and in suspended sediments is one, therefore, that remains to be determined.

Particulate and "dissolved" concentrations of hydrocarbons

In terms of overall loadings, it is more useful to express the WQB-NWRI hydrocarbon data in terms of mass per unit volume of river water, separating them according to whether the compounds were part of the suspended load or essentially free in the water. (How much of the "free" hydrocarbon material is actually attached to colloidal size sediment that does not settle under centrifuging is not known.) This distinction is shown in Figs. 6 and 7 for the 1986 data: the gap at km 901-902 emphasizes that a peak may have existed here at Norman Wells, but this is not known because of insufficient time for sampling. In any case the reliability of the Norman Wells peak in 1985 is uncertain, given that the samples were taken in shallow water close to the right bank rather than in the main deepwater channel.

The two patterns of downstream change are similar, though the changes in the PAH total are more marked. Moreover most of the PAH compounds are not bound to sediment, though the amount that is involved in the suspended load increases downstream towards the Delta. The marked decrease of PAH's in the water at Wrigley (km 577) does not seem to be entirely due to dilution of upper Mackenzie water by the Liard River. The Liard flow was only about 6500 cubic metres per second (cms) at the time of sampling, compared to the Mackenzie (downstream of the

confluence) flow of 14500 cms, i.e. about 45% of the combined flow. Simple mixing of the two waters would (based on on the data in Table 7) have yielded a PAH count downstream of 1134 ng/l, substantially in excess of the figure of 303 ng/l at Wrigley.

On the other hand, this may be a misleading analysis. As documented by Mackay (1970), when the flows of the Liard and upper Mackenzie are approximately equal, mixing remains incomplete far downstream from the confluence, and there is strong lateral change, even at Wrigley, from Liard water in the left half of the channel to Mackenzie water in the right half. Though sampling was done at the mid-point of the deep channel at Wrigley (Tisdale and DuVal, 1987), it would seem likely that most of the water that was sampled originated in the Liard rather than the upper Mackenzie. This view is based on the concentration of sediment (83 mg/L), only slightly less than that in the Liard (87 mg/L) and substantially greater than upstream of the Liard confluence (11 mg/L) (Table 6). Further downstream, at Halfway Island (km 848), however, there is no increase in the PAH level (as would be expected with increased mixing of the upper Mackenzie and Liard water), though the pattern is complicated here by tributary inputs of water and sediment from the Redstone and Keele rivers. Clearly, any interpretation of the fate of sediment and hydrocarbons downstream of Fort Simpson has to take into account the poor mixing of the two major water sources in designing the sampling stategy.

Downstream of Norman Wells, the data (Figs 7,8) indicate two changes: an increase in the percentage of hydrocarbon material in sediment form; and a general decrease in total levels. Because the same parcel of water was not sampled at these sites as it travelled downstream, it is difficult to know how much of this change is due to differences in the source of water and how much is due to changes within a given water parcel. Examination of the discharge data for the Mackenzie at Fort Simpson (10GC001) during 1986, however, shows that discharge was relatively steady at 14000-15000 cms during the third week of June, rising to 20000 cms only after the end of the sampling session. The indicated changes downstream may, therefore, be more reliable than at first thought. The data could be taken to indicate a gradual loss of hydrocarbons from the river as, firstly, adsorption occurs by the suspended load, and secondly, parts of the suspended load settle out on the bed in backwater areas and on floodplain and deltaic tracts of land.

Data from the Delta and Beaufort Sea

Results of the IOS work offshore in the estuary and in the Beaufort Sea are not yet available. All normal alkanes and all PAH compounds sampled by WQB-NWRI were determined also by IOS, though differentiation between particulate and water components was done by filtration and not by centrifuging. The methods are unlikely to give the same results on a given specimen, and some

method of correction will be needed if the two data sets are to be compared. In any case, only few data are available at the mouths of the Mackenzie. Arctic Laboratories did some sampling of Delta distributaries in April 1985 and February 1986 (Erickson and Fowler, 1987); and the Institute of Ocean Sciences sampled the three main Delta channels in the summer of 1987, concurrent with their offshore work.

The role of the Mackenzie River wash load in terms of adsorption of hydrocarbons, its degree of control on the timing and geography of inputs to the Beaufort Sea, and the extent of "undersaturation" of suspended sediment (with respect to hydrocarbons) as it enters the Sea, are thus matters of some importance to parties working offshore. Currently the data available from river sampling are quite inadequate to assist in the interpretation of offshore studies.

(d) RECOMMENDATIONS

While the initial studies by WQB-NWRI have been extremely useful, it would seem that the time is now ripe to establish fixed sampling stations that are monitored on a regular basis. In this way, genuine comparisons can be made between sites, and changes are more easily interpreted in terms of, for example, dilution effects due to inflow of "clean" tributary water, deposition or augmentation of hydrocarbon loads between sites, etc. In particular, there appears to be little known about the stability of hydrocarbons in transit along a watercourse, notwithstanding its obvious importance in the context of spills.

> 4.1.1. Suspended sediment sampling just upstream of Arctic Red River (10LA003) should be broadened in scope to include sampling of both water and sediment for analysis of hydrocarbons, throughout the year, in order to assess the changing flux of hydrocarbons to the Delta and the Beaufort Sea, and the degree of association with the wash load. Sampling also be undertaken at the mouths of Delta distributaries identified as part of Recommendation 1.

Comparison of the two data sets should indicate (a) the amount of settling of hydrocarbons within the Delta; and (b) the feasibility of using just one site (10LA003), rather than three, for assessing inputs to the Beaufort Sea.

> 4.1.2. Sampling of water and suspended sediment should be undertaken at the mouth of the Liard, and on the Mackenzie upstream of the Liard, at Wrigley, at Norman Wells and at Fort Good Hope for measurement of the concentration of selected hydrocarbons.

Sampling should be undertaken throughout the year to identify seasonal patterns, changing importance of dissolved and suspended phases, and to permit computation of monthly yields. The sites indicated either belong to the existing WSC sediment sampling programme or are recommended for inclusion in it in the next section (5).

Throughout this work, great care will be needed in sampling to ensure that mean values for cross-sections are reliable, taking into account lateral non-uniformity in the flow. This will be particularly important at Wrigley and at Norman Wells. At Norman Wells, care will also be needed to ensure that mean values are not unduly influenced by sampling adjacent to localized natural seeps. In both cases, a prior sampling program is suggested to determine the spatial pattern of variability before selection of the routine monitoring sites.

The same recommendation could also be made in terms of along-channel changes in concentrations: there is, after all, no assurance that the sample patterns of Fig. 5 actually show the true downstream pattern of change during those two seasons. But this would be a massive logistical exercise. On the other hand, it would be worthwhile, in some of the initial periods when sampling is being undertaken at the regular sampling stations, to have specimens taken at intermediate sites along the length of the river in order to assess how well the chosen stations represent the actual along-river pattern of change. A site near Halfway Island (to obtain data upstream from Norman Wells) would seem to be essential given the pattern in Fig. 5: a location at Fort Norman would have the advantage of being upstream of the entry of the Great Bear River and thus reduce problems due to lateral non-uniformity. The peculiar peak in PAH concentration of the water at km 1142 (Fig. 8) suggests that additional points may be needed upstream and downstream of Fort Good Hope. In short, far more needs to be known about the spatial variability of hydrocarbon concentrations in the Mackenzie before the representativeness of any sampling stations can be accepted.

It would also seem sensible to partition sediment into discrete size classes prior to hydrocarbon analysis. Given that fluctuations in the percentage of fine sand in the sediment will produce fluctuations in overall hydrocarbon concentration - even in the absence of changes in the hydrocarbon status of the silt and clay - this precaution will allow better interpretation of variability in the hydrocarbon sediment loads.

At all stations, samples of bed material should also be obtained for determination of the concentration of individual hydrocarbon compounds.

4.2. TRANSPORT OF HEAVY METALS

(a) ISSUES

Metals have long been known to pose a threat to the health of ecosystems. This is especially true in aquatic environments because of the toxicity of metals to aquatic organisms and the potential for accumulation in the food chain.

As with hydrocarbons, most metal ore mining has taken place in the basin upstream of the source of the Mackenzie in Great Slave Lake: gold at Yellowknife on the north shore of Great Slave Lake, and lead and zinc at Pine Point on the south shore; and uranium at Uranium City on Lake Athabasca. In the lower catchment, radium and uranium were produced on the shores of Great Bear Lake, and silver and copper are currently mined there. Tungsten and copper are mined north of Watson Lake on the divide between the South Nahanni and Liard rivers. According to the Mackenzie River Basin Committee (1985), metals are moved through the basin primarily in association with suspended solids, and thus, given the location of most of the mines, the major lakes have served as sinks for metals associated with mining activity.

With this perspective, it would seem that metal transport along the mainstem Mackenzie is unlikely to be a concern in the immediate future, unless development occurs adjacent to watercourses with direct access to the lower river. This does not mean, of course, that mobilization of metals from lake sediments may not take place in the future, or that some of this lake bed metal is not already available to the food chain in these lakes, but these issues are beyond the terms of reference of this study. Of more direct concern is disturbance of bed sediments (either by mining for borrow material or dredging for navigation) and the release of metals adsorbed to sediment into the Mackenzie River.

The main concern at the present time therefore would seem to be quantitative description of the present pattern of metal transport along the Mackenzie to permit assessment of the effects, if any, of human activity in the watershed in the years ahead.

(b) INFORMATION NEEDS

Most of the comments that were made in relation to hydrocarbons apply here. Information is needed on the main stem itself, in the Delta, and for contributions to the Beaufort Sea. Detection of changes along the main stem in response to tributary inputs, dilution, sedimentation etc. requires sampling stations at strategic locations along the course of the river.

(c) ADEQUACY OF EXISTING INFORMATION

In light of the wealth of mineral resources in the Mackenzie basin, and their inevitable exploitation in the years ahead, it is not surprising that concern has been expressed regarding the contamination of aquatic resources by heavy metals.

Investigations to date have determined concentrations of aluminum, barium, cadmium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, nickel, silver, strontium, thallium, vanadium and zinc, in both "dissolved" and "extractable" forms. As defined by Water Quality Branch laboratories of Inland Waters, the former refers to concentrations in water passed through a 0.45 µm filter, and thus includes free metal ions, those in solution as complexes, and those that are part of colloidal material (Mackenzie River Basin Committee, 1985, p. 94). The term "extractable" represents both "dissolved" material and that which is associated with solids (organic as well as inorganic) and which may potentially be released to solution. This "particulate" material includes not only metals that are sorbed to the surface of minerals, but also some of the metals incorporated in the mineral crystalline structure. Thus, while "extractable" concentrations are less than "total" concentrations (derived by complete dissolution of the particulate components of a suspension), they do, nonetheless, yield an overestimate of the amount of potentially bioavailable metal.

The data were collected during the 1960's and 1970's, by various federal and provincial agencies, on a quarterly or monthly basis. Samples were usually taken in midstream with depth integrating samplers. The data indicate that metal concentrations in river water in the basin are at "natural" levels, often below the level of detection. Iron, aluminum and manganese are almost entirely tranported in association with the wash load; copper, chromium, lead and mercury were found to be largely (55%-84%) in the particulate phase. Arsenic, often found in wastes from industry and mining activity (Hem, 1959) is reported to occur in elevated concentrations in the sediment of Yellowknife Bay, from gold mining waste, but no data appear to be available for the mainstem Mackenzie. Erickson and Fowler (1987) report that arsenic in the Delta channels was very low (much less than in seawater in the Beaufort Shelf) and 75-85% of it was "dissolved" rather than particulate. Their data refer to winter flow conditions only.

The data published by the Mackenzie Basin River Committee (1985) cover the entire basin both upstream and downstream of Great Slave Lake. Data for the lower basin are summarized for the main stem at Fort Providence, Wrigley, Norman Wells and upstream of Arctic Red River (all at regular WSC gauging sites), as well as for the Liard and Great Bear rivers at their mouths. However, in most cases, data were not available for individual sites, but merely grouped by subbasins. The maximum concentrations of extractable metal measured exceeded the guidelines for

the protection of freshwater aquatic life in both the Liard and Mackenzie subbasins for chromium, copper, lead and zinc; silver was also above the limit in the Mackenzie and copper above the limit in the Great Bear Lake subbasin. In fact mean levels for copper exceeded the guideline limit in all three subbasins.

A comparison of metal concentrations in the winter suspended load of Delta channels and in surficial sediments of the Beaufort Sea shelf was reported by Erickson and Fowler (1987). They noted that concentrations of all metals in winter river particulates, collected by filtration or centrifugation, were higher than concentrations in the shelf sediments. They concluded that "either winter particulates from the river lose metals before or after deposition on the shelf, or summer particulates have lower trace metal concentrations and dilute the concentration of particulates from the winter months."

A key point here may be particle size, because trace metal concentrations in sediment are known to increase in finer material. Winter river particulates are very fine; summer loads would be expected to be coarser. Moreover, the river-shelf comparison was not stratified on the basis of grain size. The point is clear that - once again - collection of sediment data solely for concentration values is inadequate. In any interpretation of the transport and fate of metals (just like hydrocarbons and nutrients), data must be provided for the grain size distribution of the sediment.

A major problem with metal data is their interpretation in terms of potential toxicity to organisms: there is no unambiguous measure of bioavailable metal. Wagemann et al. (1977), for example, showed appreciable variation in the metal concentration of leachates from suspended sediment taken from the Redstone and the East Delta channel, depending on the extraction solutions used. Until further research in laboratory procedures produces more meaningful indices, the impact of metals in river water on the aquatic ecosystem will not be easily determined.

Nonetheless, it is clear that benchmark data are needed to characterize the level of metals being released from the Mackenzie basin into the main stem, the Delta and the Beaufort Sea, prior to accelerated development of the watershed. The data summarized by the Mackenzie River Basin Committee (1985) are not easily interpreted in the context of the mainstem Mackenzie because of their grouping spatially, and their presentation only in terms of means and ranges. Prior to making definitive recommendations for further work, this data set would have to be examined in more detail, in terms of specific metals, actual sites and sampling times. These data are available in a report published by the Water Quality Branch (1981) which formed the basis for the interpretive report of the Mackenzie River Basin Committee (1985).

(d) RECOMMENDATIONS

Notwithstanding the precautionary comments above, it would seem that additional sampling should be undertaken at certain sites. These should be the Mackenzie River upstream of Fort Simpson (10GC004); upstream of Arctic Red River (10LA003); and, if possible, at outlets of the Mackenzie Delta distributaries as indicated in Recommendation 1. The first site would allow monitoring of metals not only from Great Slave Lake, but also from that reach of the Mackenzie (upstream of Fort Simpson) that will experience the greatest dredging activity in the immediate future. The 10LA003 site allows monitoring of water and sediment as it enters the Delta en route to the Beaufort Sea.

4.2. Routine monitoring of heavy metals in solution and suspension be undertaken on the mainstem Mackenzie at stations 10GC004 and 10LA003 to establish background concentrations under a variety of flow conditions. The work should be supplemented by measurements at the mouths of the three main Delta distributaries (See Rec.#1) and timed to coincide with years in which measurements are made offshore. Planning should take into account the precautions noted below.

Because metal analyses have already been undertaken for the Beaufort Sea by DFO, and will probably continue in the future, as well as in the river basin by other federal and provincial agencies, it is extremely important that sampling procedures, methods of storage and laboratory analysis be the same within the basin and offshore. Moreover the exacting requirements for sampling and storage, in the case of some of these metals, may require that onshore and offshore sampling and analysis be done by the same parties. Thus direct involvement of Water Resources Branch staff in the sampling programme may be minimal.

On the other hand, it is clearly advantageous to have this work done at regular WSC sediment sampling sites, so that the data from these metal samples can be seen in an appropriate context: discharge conditions at the time of sampling in relation to the long term discharge record; sediment concentrations at the locations and times of sampling in relation to spatial variability of concentrations (and particle size) within the cross section, and fluctuations over time, etc.

4.3. CONTAMINATION OF FISH BY WATER AND SEDIMENT

(a) ISSUES

Movement of hydrocarbons and heavy metals within the mainstem Mackenzie is currently an issue to the extent that it may be related to impaired fish quality reported by local fisheries on the lower river. Comments have been made by residents of Fort Good Hope and other communities along the lower river that, in recent years, the liver of the burbot (a traditional food item in many northern communities) has often been unusually small, dark-coloured and unsuitable for consumption. A second comment has been that the flesh of whitefish has become excessively "watery" in consistency. The study by Lockhart et al. (1987) supports these complaints.

Whether or not these changes in fish condition are related to oil industry operations at Norman Wells, as supposed by some, and whether or not they are sediment-related issues, are much more difficult to establish.

(b) INFORMATION NEEDS

Three approaches to this problem are possible. One is an experimental one in which healthy fish are kept in water that is contaminated with specific compounds, either free in the water or sorbed to suspended sediment at concentrations found in the Mackenzie system. A second is the pathological one in which unhealthy fish are compared with healthy specimens in order to discover differences in levels of contaminants. The third is epidemiological in which the geography and timing of the contaminated fish are examined. All three approaches have been implemented recently.

(c) ADEQUACY OF EXISTING INFORMATION

E.V.S. Consultants Ltd (1986) have undertaken experiments in which burbot and Arctic grayling were exposed for ten days in cages at sites upstream and downstream from known point sources of hydrocarbon inputs, and subjected to analysis. According to abstracts available, however, further investigations are still required to confirm the applicability of the technique in demonstrating relationships between liver histopathology and hydrocarbon exposure.

Lockhart et al. (1987) have approached the problem both pathologically and epidemiologically; their conclusions were also far from definitive. They note that fish from the Mackenzie River show widespread contamination by several organochlorine compounds (toxaphene, chlordane and PCB's) as well as by low

levels of low-boiling point aromatic hydrocarbons typically present in Norman Wells crude oil and in refined petroleum products. The most specific diagnostic test available indicated, however, that the burbot were not responding to oil pollution, although it was conceded that interpretation was difficult because of the discovery of higher levels of PCB's in the "control" population of burbot from Lake Winnepeg. They also point out that, in samples taken in the fall of 1985, fish from Fort Simpson and Fort Franklin contained these hydrocarbons at about the same levels as fish from Fort Good Hope and Arctic Red River, implying that "Norman Wells could not have been the exclusive source of these compounds" (p. 24). Finally, they note that the dark colour and small liver size are prevalent in burbot from several northern communities, outside as well as within the Mackenzie basin. In general, therefore, they suspect that the liver condition is unlikely to be due to exposure to petroleum hydrocarbons. They also provide indirect evidence to indicate that, although reported only recently, the liver condition may have been present at least as far back as the early 1970's.

Metals do not appear to be implicated in the problem either. Neither nickel nor vanadium (the major metals in Norman Wells oil) was found in whitefish muscle or burbot liver.

(d) RECOMMENDATIONS

Lockhart et al. (1987) have already provided a comprehensive summary of previous work with recommendations for additional investigations. Their approach is based on the view that the fish problems of the Mackenzie are likely to be much more widespread in northern Arctic communities than simply the Mackenzie River.

Bearing in mind the mandate of the present report, the only additional point is whether or not sediment is implicated in the problem. The evidence to date suggests that it is not. In the first place, virtually all the PAH's (but not the alkanes) in the lower river occur in the water, rather than in the suspended sediment. Secondly, preliminary data from DFO (Lockhart et al., 1987) indicate that contamination of fish with aromatic hydrocarbons in the Fort Good Hope area is substantially greater in winter than in summer. Winter concentrations of suspended sediment are extremely low; in contrast, evaporation of hydrocarbons free in the water is impeded by ice cover at this time, so that "dissolved" concentrations should be higher. Nonetheless the source of these hydrocarbons has not yet been identified, and it would seem prudent to at least examine the hydrocarbon content of the bed sediment in the Fort Good Hope area. This has already been suggested previously (Rec. #4.1), not only for Fort Good Hope, but at all stations involved in sampling suspended sediment.

5. SOURCES OF SUSPENDED SEDIMENT IN THE MACKENZIE BASIN

(a) ISSUES

The importance of inputs of suspended sediment to the delta at Point Separation, and beyond to the sea, has already been noted. Short term prediction of inputs may be possible solely on the basis of statistical relationships between concentration and water discharge, time of year, temperature etc. at stations near the input sites on the Mackenzie, Arctic Red and Peel Rivers. Such relationships are unlikely to remain stable over a long period of time, however, because of changes in supply rates from the source areas due to changes in environmental conditions. Partly for this reason, but more importantly in order to assess the impact of changes in the source areas, it is desirable to have a clear picture of the proportion of the downstream suspended load originating in different subbasins.

One obvious example of this is the need to be able to accurately predict the reduction in suspended load input to the Delta that would result from damming of the Liard for the development of hydroelectric power. A less obvious point would be the magnitude of suspended load increase in the event of permafrost degradation (due to CO_2 warming of the atmosphere) and the resultant increase in bank slumping along the Mackenzie main stem. Another is the impact of forest fires on thaw of ground ice and increased delivery of fine sediment to rivers from gullying and bank collapse. A further one is the recently announced proposal for increased logging in the Liard basin.

In short, in order to understand what controls fluctuations in suspended sediment loads at the downstream end of the Mackenzie, and therefore to be able predict future loads, quantitative knowledge of the contribution of different source areas is needed. In addition, in any attempt to understand changes in concentration of adsorbed materials, whether over time or spatially, a breakdown of the total into its component supply areas is needed.

(b) INFORMATION NEEDS

Ideally, data are required for suspended sediment yields (annual totals broken down by month and by particle size) for all major tributaries, measured as close as possible to the confluences of these rivers with the Mackenzie main stem. The data would need to relate to a sampling program that had been long enough to develop useful statistical relations between concentration (by particle size) and flow characteristics (as well as time of year). In this way, predictions for future years could be made using those relationships.

Information is also needed on how much sediment is contributed to the annual suspended load of the Mackenzie from sources along the main stem itself.

In addition, data would be needed on the amount of sediment from different source types (bank erosion, landslides, gully erosion, slope wash etc.) both within subbasins and along the main stem.

Finally, some indication is needed of the amount of suspended sediment supplied by tributaries and the main stem that is deposited on the bed of the Mackenzie. Given the power of some of the west bank tributaries, it seems likely that some of their suspended load is actually bed material load rather than wash load. In turn, given the lower gradient of the main stem, it seems probable that some of this suspended bed material may settle out to become bed load in the main stem rather than being moved in suspension. This kind of information requires careful comparison of particle size data in the suspended loads of tributaries and the main stem. It also needs grain size comparisons to be done at different sites along the length of the Mackenzie. Comparison with grain size characteristics of the bed material in the main stem are also needed (these data are examined in Section 6).

(c) ADEQUACY OF EXISTING INFORMATION

Upstream of station 10LA003 (Mackenzie River above Arctic Red River), the only suspended sediment data available for the Mackenzie are at Norman Wells (10KA001: 1973 only) and upstream of the Liard (10GC004: 1972-75). The only data for tributaries near the confluence with the main stem are for the Harris (10GC002: 1972-76), the Liard (10ED002: 1972-76; 1979-84), the Martin River (10GC003: 1973-76), the Redstone River (10HB001: 1973 only), the Trout (10FA002: 1973-75) and Willowlake River (10GB001: 1973-74 only). The yields of the Harris, the Martin, the Trout and the Willowlake are so small that they are of little significance in any interpretation of the sediment load of the Mackenzie.

Inputs from the Liard River

Of the others, only in the case of the Liard are sufficient data available to allow derivation of reasonably reliable statistical formulae for the prediction of sediment concentrations. The actual sediment rating curve of the Liard near its mouth is itself quite strong, though scatter occurs at high flows, especially in association with floods from intense summer storms (BC Hydro, 1984). Table 8 shows the frequency of sampling at the Liard mouth site, and indicates a good coverage including early summer months.

BC Hydro (1984) has produced a sediment rating curve for the Liard based on data for 1972-79, and used this to estimate annual loads for the period 1973-79 (Table 9). It should be noted that the equation used was the best fit regression using logarithmic transformations. There is no indication that it was adjusted to

rectify bias in the prediction of actual (not logarithmic) concentrations, hence the loads predicted would be underestimates of actual loads. An unbiased estimate of the concentrations can be obtained, but requires knowledge of the standard error of estimate (Ferguson, 1986); this was not given in the report.

In addition, considerably more data have been gathered in the 1980's and warrant analysis. For example, BC Hydro's (1984) predicted average annual suspended load on the Mackenzie above Arctic Red River (10LA003) for 1973-79 is 109.3 Mt. This contrasts with that of Lewis (Table 1) for the 1974-83 period of 73.6 Mt (uncorrected for bias), adjusted to 88.2 Mt to eliminate bias. If the same discrepancy between the 1973-79 and 1974-83 loads exists on the Liard, then BC Hydro's estimates for the Liard are probably too high. On the other hand, it should be noted that the BC Hydro regression for 10LA003 was based only on the 1973 and 1974 years; the latter had abnormally high August concentrations because of intense rainstorms. Thus BC Hydro's apparent overestimates of the 10LA003 load may be primarily the result of having used only two years of data for the 10LA003 regression (in contrast to six years in the case of the Liard); they do not necessarily indicate that conditions in the 1970's, as a whole, were different from those in the 1980's. In that case, their estimates for the Liard may be reasonable, provided that they are increased to remove the logarithmic bias.

At best, then, present data in the Mackenzie basin appear to be adequate to assess the fraction of the Mackenzie's suspended load at 10LA003 that is contributed by the Liard (assuming no settling of Liard sediment). Estimates by BC Hydro (1984) indicated that the Liard accounted for 17-75% of the load of the Mackenzie at 10LA003 between 1973 and 1979, averaging slightly more than 40 percent. The major part of the Mackenzie's input to the Delta is thus from sources whose contributions have yet to be assessed. Moreover, great care must be used in comparing the Liard load with that of the Mackenzie at 10LA003. Tables 1 and 9, for example, reveal several interesting points. In particular, there is the discrepancy between the average May load on the Liard of 4.1 Mt and that at 10LA003 of 17.8 Mt in the same month. While many factors may contribute to this difference, the possibility of an overestimate of the 10LA003 load (because of backwater effects on stage, noted in Section 2) should be kept in mind.

In parenthesis, it should be noted that similar studies undertaken by BC Hydro at the potential Beavercrow power site indicated that, during 1973-79, the Liard at that site accounted for only 20% of the Liard suspended load at 10ED002 (the bulk of the 10ED002 load originating from the Fort Nelson and S. Nahanni tributaries) and only 9% of the Mackenzie's suspended load at 10LA003. This latter figure may itself be on the high side because much of the Beavercrow load, being coarser than that sampled at 10LA003, may settle out during its travel downstream. (However, the reliability of the particle size data for 10LA003

is uncertain, given that it pertains - in most cases - only to the top 4.5 metres of the flow, and hence is probably finer than the true suspended load.) It is just as plausible that this 9% figure is an underestimate; if Lewis's figure for 10LA003 of 88.2 Mt (Table 1) is used, the percentage contribution at Beavercrow would be 10.7; it would be even greater if the early summer loads of 10LA003 have been overestimated because of backwater effects on water discharge estimates.

The effect of changed flow regime on the Liard must also be considered. The assumption is frequently made that the bulk of the Mackenzie suspended load is wash load: i.e. sediment for which the concentration in the flow depends primarily on availability rather than on the intensity of channel hydraulic forces. This assumption may not be completely valid in all cases: it seems likely that the relative balance between wash load and bed material in the suspended load varies in the different reaches of the Mackenzie (Part One: Section 2.2). Indeed, even at 10LA003, it appears that suspended sediment over the thalweg may include substantial bed material from upstream, given that echo soundings there indicate a hard bed (Church, 1988, pers. comm.). Thus the impact of damming the Liard may be more than simply trapping of sediment. The changed flow regime, with reduction of summer peak flows, may also be a factor, producing a reduction in the bed material load. However, the sandy bed material load at Norman Wells amounts to about 1 Mt per year only (Church et al., 1986); the total suspended load at 10LA003 is of the order of 90 Mt per year; hence even this effect on the suspended load at 10LA003 is probably insignificant.

The comments above should not be interpreted as meaning that a Liard dam would have no impacts on the Mackenzie. Its effect on the bed material load, though small relative to the total load, may nonetheless effect channel morphology downstream of the Liard mouth. Brief comments on this aspect are made in Section 6.

Downstream of the Liard confluence, fine sediment is supplied to the Mackenzie by erosion of banks along the main stem and by tributaries. The relative importance of these two sources is unknown. The two topics are summarized below.

Inputs from the banks and valley sides of the main stem

As far as scour of banks along the main stem itself is concerned, it is clearly impractical to accurately determine contributions along the full length of the Mackenzie. At the same time, those areas in which the river is cut into thick deposits of fine grained glaciolacustrine sediment are known from the surficial geology maps, and it would be a worthwhile exercise to attempt to determine how much sediment is contributed by erosion of banks in these, the most sensitive, areas.

Inputs from tributaries between the Liard and Arctic Red

With regard to tributary contributions, thorough sampling of all major tributaries is not practicable. A preliminary estimate of tributary contributions is shown in Table 10. These estimates are based on a simple index of stream power (normally taken as the product of discharge and stream gradient). Morphometric data for various basins tributary to the Mackenzie were provided by Thakur and Lindeijer, 1973). These data include basin size, maximum ground elevation and mean tributary slope. Assuming that discharge is largely controlled by basin area and rainfall/snowmelt amount, and that the latter varies in the Mackenzie area primarily according to elevation, then a rough estimate of stream power is given by the product of the three morphometric variables listed above. The approach thus provides a quick ranking of the basins in terms of likely sediment load, assuming that sediment availability (and ease of entrainment) is constant between basins.

The approach has been extended in order to provide first estimates of actual annual loads. The map of suspended sediment yields for Canada (Stichling, 1974) suggests that, apart from above-average yields in the Peel basin, the rest of the Mackenzie area has more or less uniform yields (on a unit area basis). With this perspective, Arctic Red could be taken as a "standard", for which its mean annual load is known (Section 2), and the other subbasins could then be scaled up or down, according to their values of the stream power index relative to that of Arctic Red.

While the approach is somewhat crude, the estimate for the Willowlake, for example, is comparable (0.3 Mt) with the actual load of 0.1 Mt "measured" in 1973 based on WSC data. Moreover, the results (Table 10) are intriguing. Ignoring the Arctic Red, and the Peel (for which the "actual" mean load is substantially higher than the predicted value, as expected), the rest of the tributaries produce a combined predicted annual yield of 41.2 Mt. The mean annual suspended load of the Liard (the remaining significant tributary) was estimated by BC Hydro (1984) as 47.4 Mt for the 1973-79 period. The sum of this value for the Liard, and the combined estimates for all other tributaries to the Mackenzie, upstream of Arctic Red River, is 88.6 Mt, virtually identical with the estimate of the annual load of the Mackenzie at 10LA003 given by Lewis (in prep.) for the 1972-83 period (Table 1).

(d) RECOMMENDATIONS

The first major task is to assess the accuracy and character of the sediment data for the Mackenzie's most important tributary, the Liard at 10ED002.

5.1. A full sediment station review should be undertaken for the Liard (10ED002) to find out whether there are grounds for suspecting any bias in the data, and to find out if precision of predictions can be increased by stratifying the data (e.g. by month) or by inclusion of additional variables (e.g. temperature, rate of change of discharge, etc.).

Hopefully, accuracy of predictions will be sufficiently good to allow abandonment of a full sampling programme at this site (until major land use changes occur in the basin) and replacement by spot checks to assess the stability of the predictive equation.

Turning attention back to Table 10, if the sediment loads there are in fact accurate, they imply that the suspended sediment load contributed by bank scour and slope processes along the main stem itself is negligible. This conclusion should be verified, simply and inexpensively, by examination of aerial photographs, although its priority is not high.

5.2. A search should be made of the listings of large scale aerial photographs in those regions of the Mackenzie Valley flanked by unstable glaciofluvial lacustrine muds. Comparison of aerial photographs should be made, where available in the same reach over a given period of time, to enable some assessment of the average annual contribution to the Mackenzie load from instability and erosion of the valley sides.

Between the Liard and the Arctic Red, Table 10 reinforces subjective impressions that the key tributary rivers are the Keele, Redstone, Root, Mountain and North Nahanni. Ideally sediment inputs would be determined for all of these tributaries (and perhaps the Johnson and Dahadinni as well). In practice this would prove to be a formidable logistical task, especially given the likely instability of stage-discharge rating curves at the mouths of these rivers. There is, in fact, already a miscellaneous sampling program on the Mountain River at 10KC001, but the site was chosen on the basis of suitability for a hydrometric station, and is far upstream of the river mouth.

Nonetheless, some indication of the collective inputs of the North Nahanni and Root rivers, the Redstone-Keele rivers and that of the Mountain River could easily be obtained by establishing additional sediment stations on the main stem at Wrigley, Norman Wells and Fort Good Hope (Fig. 8).

5.3. Regular suspended sediment sampling programmes, comparable in scope with that at 10LA003, should be established at Wrigley, Norman Wells and Fort Good Hope for the purpose of assessing tributary inflows of sediment.

Establishment of stations at Wrigley and Fort Good Hope has already been recommended (4.1.2) as part of the study of hydrocarbons. Implementation of a regular suspended sediment sampling programme at Wrigley is also advocated in Rec. #6.5.3 in the belief that much of the bed material of the Liard-Mackenzie confluence is thrown into suspension in the Wrigley reach. (Frequent particle size analyses will be needed to allow partition of the bed material load and wash load in suspension at Wrigley.) Resurrection of the sampling programme at Norman Wells is also suggested in Rec. #7 in connection with estimates of infill rates of the proposed dredging channel at that location. A gauging station already exists at Norman Wells (10KA001) and water level recorders appear to be already in existence at Wrigley and Fort Good Hope.

Because the concentrations in the Mackenzie upstream of the Liard are small, the upper river contributes only a small load to downstream. With concentrations of about 20 mg/L, and discharges of the order of 6,000 cms, this amounts to only about 10,000 tonnes per day over much of the ice free season. Admittedly this figure is comparable with spot determinations of loads on the Redstone in 1973 during a much shorter high flow period. There is, however, little incentive to extend the fairly large data set at this site on a routine basis. Additional data would, in any case, be forthcoming if Rec. #4.1.2 (dealing with hydrocarbons) and Rec. #4.2 (dealing with heavy metals) are implemented.

5.4. No further sampling at station 10GC004 be undertaken, except as part of the investigations of hydrocarbon and metal contaminants. Statistical analysis be undertaken to find out whether concentrations are capable of adequate prediction on the basis of hydrological variables.

6. TRANSPORTATION OF BED MATERIAL ALONG THE MACKENZIE RIVER

The suspended sediment load of the lower Mackenzie system was discussed in three separate sections: (1) inputs to the Beaufort Sea; (2) inputs to the Delta; and (5) sources of suspended sediment in the Mackenzie Basin. In dealing with the bed material load, it seems more appropriate to combine all three geographic reaches in one section. This section is therefore somewhat longer than earlier ones.

(a) ISSUES

Most discussion of sediment input to the Delta has concerned suspended sediment, which is assumed to be largely wash load. The fate of bed material brought in by the Mackenzie at Point Separation seems to have been largely ignored. Yet in terms of the stability of the shoreline of the Delta margins, and in terms of depth of flow along distributary channels, the magnitude and spatial pattern of sand movement through the delta need to be known.

Work at the National Hydrology Research Institute (Lapointe, 1984, 1986) has already identified several such issues. One relates to the existence of deep "scour" holes maintained by the failure of sediment to accumulate on the bed at such sites. Another concerns the abandonment of distributary channels by shoaling of bed sediment at the site of bifurcation from the main channel. The entry area to the East Channel, for example, is heavily shoaled, raising the question of future water inflows down this distributary. Interestingly, the Northern Transportation Company Limited has recently designated Kitti Channel at the exit of the East Channel to Kittigazuit Bay (km 1715-1722) as the thirteenth in a list of 26 priority dredging sites on the Mackenzie River.

More generally, the question must be asked: How quickly are the distributary mouths, e.g. Shallow Bay, Kittigazuit Bay, being infilled? Will future rates of bed material supply to the bays be able to keep pace with rising sea levels? Most data on sedimentation have been offshore beyond the 10 m bathymetric contour. Very little seems to be known about how much sand moves downstream past Point Separation and how much reaches the distributary mouths.

In addition to bed material inputs to the Mackenzie Delta, the sources of this sediment load also need to be determined. One obvious issue is the possible impact of changed flow regime and trapping of bed material, following the construction of dams on the Liard River, on bed material transport along the mainstem Mackenzie and the morphology of its channel.

Even more important in the context of the bed material load than for the wash load, there is the question of how uniform are

transport rates along the course of the Mackenzie river. Are there distinct areas of degradation and aggradation? Do tributary loads have well-defined local sinks near the confluence with the main stem, or do they become incorporated in the general load of the Mackenzie? These are general scientific questions that need to be answered in order to understand the overall behaviour of the Mackenzie River. The topic also provides a necessary framework for answering more immediate specific questions related to bed material transport noted in the next sections (7-11).

(b) INFORMATION NEEDS

Data are required as follows:

i. the rate of accumulation of sediment in the bays at the mouths of the three main distributary channels: Reindeer, Middle and East channels;

ii. the rate of bed material input to the Delta by the Mackenzie, Arctic Red and Peel rivers;

iii. the rate of accumulation of bed material within the Delta complex;

iv. the magnitude of sandy bed material inputs of the major tributaries of the Mackenzie;

v. changes in the sandy bed material load along the course of the Mackenzie due to additions (from tributaries, from channel degradation, and from settling out of the wash load) and due to losses arising from long-term accumulation of bed material on the bed (aggradation) or from conversion of some of the bed material load to wash load;

vi. locations of accumulation of gravel in the main stem and the rate of accumulation in each case.

Ideally rates would be obtained annually; in this way annual loads could be related to the hydraulic features of each year's flood events, and exisiting transport formulae calibrated. In reality, this is not possible, because the methods of measurement may only be accurate enough to depict changes, e.g. aggradation, over periods of 5 or 10 years or longer.

(c) ADEQUACY OF EXISTING INFORMATION

Data on bed material transport rates are virtually non-existent for the Mackenzie. In part this reflects the much greater difficulties of measuring bed material transport rates (compared to suspended sediment) in rivers generally. Engineering formulae do exist for predicting rates, but they are liable to errors of orders of magnitude, and, in any case,

require far more information on the particle size of bed material than is available for the Mackenzie.

With these difficulties in mind, the logical method to compute bed material transport rates is by morphometric analysis (Church et al., 1986). The approach taken recognizes that bed material does not move uniformly along a reach (as if it were on a conveyor belt), but is, in effect, shunted from zones of scour to zones of accumulation. By measuring the total amount of gross deposition in a reach (or the total amount of scour: the two amounts may in many cases balance each other), and determining the step distance of transport from scour zone to accumulation zone, the total amount of bed material passing an arbitrary cross-section in the reach, in that time interval, can be determined.

This "morphological method" of determining bed material transport was originally advocated by Neill (1971), and illustrated by reference to other rivers in western Canada. The primary needs for implementing the approach are bathymetric charts of the river reach separated by a time period that is long enough (usually 5 to 10 years) to allow sufficient change in the bed morphology relative to the resolution of the surveys. The work by Church et al. (1986) was a bold, pioneer, attempt to determine bed material loads on the Mackenzie, in the vicinity of Norman Wells, using the morphological method. Opportunities would seem to exist for expanding it to other areas of the river, given the availability of bathymetric surveys by the Canadian Hydrographic Service (CHS).

Substantial refinements can be made in the actual methods used. In particular, where repeat CHS charts are available for a given reach, rather than simply compute changes in mean depth for successive 2 km long sub-reaches, and use these values to estimate short-term degradation and aggradation in the whole reach (and thereafter bed material transport rate), more sophisticated computer software should be utilized. This would allow, for example, interpolation of depths at actual sounding points to intersections of a superimposed grid; repetition of the process with the data of a later survey; and mapping of actual changes in depth at grid intersections. The latter is not only conveniently used for calculating gross volumetric change in the reach with more accuracy, but also allows the spatial pattern of change to be shown. That pattern is extremely important in understanding the mechanisms of bed material transport. Software for undertaking this type of analysis is available from various sources; the Water Resources Branch has in fact developed its own mapping system for this purpose (McIlhinney, 1987).

In discussing bed material transport along the main stem, it is useful to refer to both a map of the river course (Fig.3) and its long profile (Fig. 4). (These outline a subdivision of the Mackenzie into twenty distinctive reaches, based on channel morphology and low-water gradient: Part One, Section 2.2).

Discussion of the bed material load below deals primarily with the sand fraction, and is organized geographically, beginning with the downstream reaches. Information pertaining to zones of gravel bed material is discussed in item #6.

1. The Delta-Beaufort Sea margin.

Virtually no data exist for this area, and yet, since the bays at the mouths of the delta distributaries act as sinks for bed material, the opportunity clearly exists for assessing inputs by repeated surveys. Unfortunately no reliable bathymetric survey exists; one is urgently required. Because of the difficulties of vertical control on water (tidal and storm surge effects, wave chop), the problems of grounding in shallow water, and the turbidity of the water in the open-water season, conventional echo-sounding by boat may be difficult. An alternative procedure would be to attempt soundings from a smooth, level ice surface (by snowmobile) in the winter. Unfortunately, this also has major drawbacks: the procedure is slow and yields only spot soundings rather than complete profiles; there are major difficulties of interpretation in areas where the ice cover is grounded; and weather conditions and fewer daylight hours make winter fieldwork generally more expensive than summer work.

2. Inputs to the Delta by the Mackenzie, Arctic Red and the Peel Rivers.

Information on bed material delivery rates to the Delta at Point Separation is also virtually non-existent, yet it is a vital concern for reasons already given. There are, however, sufficient hydrometric data, at least in the case of the main stem, to enable good estimates of these loads.

The Mackenzie between km 1350 (Barrel Crossing) and km 1435 (just upstream of Lower Ramparts) displays a classic pattern of alternating pool-riffle units (Fig. 9). These are clearly displayed on existing CHS field sheets for Charts 6425 and 6426 surveyed in 1973 and 1977/78. Preliminary manual computation of morphological change on two such units indicates an average transport rate of about 4.5 million cubic metres per year in this period. This is tentative: manual calculations are time consuming and liable to more error than computer analysis.

The downstream part of the Peel River has been sounded fully only once: (Charts 6440 and 6438) in 1973. There is some semblance of an alternate pool-riffle pattern, especially in a 15 km stretch at and upstream of Fort McPherson, but depth changes are not as strong as on the Mackenzie. No bathymetric data at all are shown on the CHS chart of the lower Arctic Red River. A well-developed meander belt exists on the Peel River between Husky Channel and Peel Channel which may be more amenable to morphological analysis (Neill, 1971), but no such pattern exists on the lower Arctic Red River.

3. Accumulation within the Delta

The gross volumetric accumulation can be derived simply by comparison of the results from (1) and (2) above. On the other hand, what also matters is some idea of the spatial distribution of aggradation within the delta distributaries. Apart from selected key areas, such as the entrance to East Channel from Middle Channel, however, it would seem sensible to defer a detailed mapping of changes within the delta distributaries until a gross figure has been obtained.

4. Sandy bed material loads downstream of Wrigley

Church et al. (1986) have provided a first estimate of bed material loads in the Norman Wells reach, indicating an average load during the 1950-1971 period of about 550,000 cubic metres per year past a channel cross-section. This was based on comparison of vertical aerial photographs, and making assumptions about the thickness of alluvium eroded and deposited. A more limited analysis was done of bathymetric surveys for Chart 6419 surveyed by CHS in 1971 and 1978: the reach was only 36 km long, however, and reservations were expressed about the statistical reliability of the sample data and procedures.

The preliminary estimate of sandy bed material transport on the lower Mackenzie of 4.5 million cubic metres per year (noted in (2) above) is substantially higher than that of Church et al. (1986) for the river at Norman Wells between 1950 and 1971. In part the difference may result from the above-average flows between 1973 and 1977. Nonetheless it is highly probable that long-term rates near the Lower Ramparts are greater than at Norman Wells, where the channel is not fully alluvial, but takes the form of sand bars and islands moving over a clay or till platform. In particular, the Mountain River is expected to supply a substantial addition of sandy bed material. In addition, some of the wash load at Norman Wells may have settled out as bed material in the alternate bar reach.

Set against these points, however, it seems likely that aggradation is occurring in the flat reach of the Mackenzie above Sans Sault Rapids, so that some of the load from Norman Wells may not be reaching the lower river. Some investigation is clearly needed of the pathways taken by sandy bed material before it reaches the lower Mackenzie.

Upstream of the alternate bar reach, as far as Fort Good Hope, CHS charts exist for 1972 (or 73) and 1979. Mackay and Mathews (1973) suggested that aggradation may well be occurring in the Mackenzie downstream of Fort Good Hope at the present time. It would thus seem sensible to utilize the CHS charts to produce a map of patterns of short-term aggradation and degradation in this period, and to estimate transport rates in the Fort Good Hope trench.

Upstream of Fort Good Hope, the only CHS chart with repeat surveys is 6419 (1971 and 1978). This is the chart analyzed by Church et al. (1986) from km 909 to km 945. The difference between the bed material load in this reach and that in the Fort Good Hope trench will reflect two main factors: (a) any changes in storage in bed material upstream of the Ramparts (in the Hume River Crossing reach) and upstream of Sans Sault Rapids; and (b) inputs from Mountain River. Neither is easily estimated, but they are important.

5. Transport of sandy bed material upstream of Wrigley

Upstream of Norman Wells, some partition of the sandy bed material load is needed between the upper Mackenzie (upstream of Fort Simpson), the Liard, North Nahanni, Root, Redstone and Keele rivers (Fig. 10).

The only data currently available are estimates by BC Hydro (1984) of bed load transport on the Liard, in the reach downstream of the South Nahanni, based on the Meyer-Peter and Muller formula. They indicate that, at the mean annual flood, the present rate is of the order of 5,300 tonnes per day (roughly 3,000 bulk cubic metres per day), which would decrease by about 25 percent following flow regulation. This figure is, incidentally, less than half of the rate on the Liard upstream of Nahanni Butte, implying considerable deposition, not only of the upper Liard bed load, but also that of the South Nahanni itself which enters at Nahanni Butte.

No data were given by BC Hydro for the predicted load under the full flow-duration curve, but the transport rate at the annual flood seems low: even if applied over 30 days, it would correspond to less than 100,000 cubic metres, which in turn is less than 20 % of the bed material load discharge inferred by Church et al. (1986) at Norman Wells. Many explanations for the discrepancy are of course possible, including the inputs of other tributaries. One should suspect, however, that much of the bed material load actually moves in suspension, and not as bed load, a common feature of sandy rivers (Colby, 1964).

No full CHS survey exists for Chart 6410 downstream of the Liard. Nonetheless the combined Mackenzie-Liard load could be determined from morphometric analysis of CHS chart 6411 (surveyed in 1979) provided that a new survey were undertaken.

The combined sandy bed material load of the Mackenzie, Liard, North Nahanni and Root rivers (and, by comparison, the combined input of the latter two) could be assessed morphometrically using CHS Chart 6412 which was completely surveyed in 1972 and repeated, at least between km 489 and km 511, in 1978. The reach is unfortunately short, but would provide a first estimate of the input of these rivers.

Downstream of km 511, the gradient steepens and the bed material becomes non-alluvial for 160 km through the Wrigley reach.

6. Accumulation of gravel in the Mackenzie River.

One of the distinctive features of the Mackenzie is that several west bank tributaries have created definite gravel fans in the main river. This is especially the case for the Redstone-Keele rivers in which a steep gravel-bed reach downstream of their mouths abruptly changes to a gentle sand-bed channel 75 km downstream. This reach therefore appears to act as a sink for gravel from these two rivers (but see Section 11). Measurements of aggradation and/or downstream advance of the wedge would enable calculation of present rates of gravel input. Unfortunately neither chart (6415-6416) has yet had a complete bathymetric survey undertaken. Moreover, preliminary estimates of the annual gravel yield (based on comparison with New Zealand rivers) suggest that accumulation of the load over such a vast fan surface would lead to changes in mean elevation of the bed that, even over a period of a decade, would not exceed measurement error.

On the other hand, there is no reason to believe that, in the short term, this aggradation is spatially uniform. It may well be localized just downstream of the confluences. Indeed the definite hump in the long profile at the Redstone confluence suggests that this is the case. Aggradation would be expected in years in which major rainstorm-induced flows occur in these tributary catchments, while the mainstem flow is relatively weak. Bathymetric mapping in the reach would at least provide a benchmark survey so that the gravel yield of future high-return period floods could be determined.

Summary. Preliminary indications for the Norman Wells reach and the alternate bar reach of the Mackenzie upriver from the Lower Ramparts are that comparison of bathymetric charts constitutes an efficient, and probably fairly reliable, means of estimating bed material transport rates. The reliability would seem to be at least as good as alternative procedures such as direct measurement and prediction by formulae. In several key areas, repeat chart surveys have already been done on the Mackenzie; in other areas, additional surveys are needed. The bulk of the recommendations below deal with the use of this "morphological" approach to estimating bed material transport.

(d) RECOMMENDATIONS

A proposed sampling programme for sandy bed material load is illustrated in Fig. 10. It emphasizes five key areas:

(1) distributary mouths at the outer margin of the Delta;
(2) inputs to the Delta from the Peel and the Mackenzie upstream of the Lower Ramparts;
(3) inputs to the start of the Fort Good Hope trench;

(4) the sediment budget between Norman Wells and Fort Good Hope;

(5) sources of the sandy bed material load upstream of Wrigley.

The numbering system used below for these recommendations corresponds to that employed in the previous analysis of available data (c), for ease of cross reference.

> 6.1. An assessment should be made of the feasibility, accuracy and cost of a bathymetric survey of the bay areas. If the results are encouraging, a survey should be undertaken as soon as possible, followed by a resurvey in about 10 years time.

It should be recognized that any attempt to undertake this survey by echo-sounding from the water surface would require a prior survey to be done of the temporal-spatial changes in the level of the water surface during typical tidal cycles.

> 6.2.1a. Existing CHS field sheets for 1973 and 1977/78 for Charts 6425 and 6426 should be digitized and the data file subjected to analysis to determine spatial pattern of scour and fill over the pool-riffle system, allowing calculation of the mean bed material transport rate for the period.

It should be remembered that the CHS field charts are "shoal-biased", i.e. data points are concentrated in shallow areas, rather than being spread uniformly over the channel. Volumetric calculations will therefore be liable to an additional error because of this. On the other hand, the extra time involved in digitizing the original sounding rolls and positioning data may not be warranted if the error is small. A comparison of the two approaches on one chart would be useful.

> 6.2.1b. An immediate resurvey should be requested of CHS for km 1350-km 1435 (Charts 6425-26) to allow calculation of bed material yield since 1977/78. Data should be provided in digital form.

According to Lewis (in prep.), the Arctic Red accounts for less than 6 per cent of the suspended load entering the Delta, and, given this (and by inference), determination of the bed material load of the Arctic Red must be low priority. On the other hand, the same assumption cannot be made of the Peel River, given its apparently high suspended load.

6.2.2. Attempts to calculate the input of sandy bed material from Arctic Red River should be deferred for the moment. Calculation of the Peel load should be attempted using morphometric analysis of meander migration in the reach between Husky and Peel channels.

Suitable photographs for this work on the Peel were taken in 1950 and 1971/72 have been examined previously by Outhet (1974a,b) and should be supplemented by a new coverage. The morphometric approach should be complemented by field investigation of bank heights and stratigraphy, including ice content, and bar sediment, to ensure that the calculated yield refers entirely to bed material.

The data provided above would indicate present mean rates of transport of bed material over periods ranging from 5 to 20 years. In the case of the lower Mackenzie, this is inadequate, and it would be very useful to have data for annual loads of bed material. Clearly, data collection cannot be done every year on a long term basis. On the other hand, the opportunity definitely exists to establish a relationship between annual bed material yield on the lower Mackenzie and hydraulic conditions in that year. In effect, this would amount to a bed-material sediment rating curve, or, alternatively, testing of various bed-load formulae.

The magnitude of change in the pool-riffle reach between km 1350 and km 1435 is sufficient to warrant annual resurveys of selected pool-riffle units. These units are about 12 km long. Visual comparison of changes on the 1973 and 1977 sheets indicates a mean annual travel distance of about 300 m; though this may be above-average (given the high flows in that period), it suggests that annual surveys of a 15 km reach, with transect spacing of about 50 m, would give results of acceptable accuracy. It should be recognized that the extra cost in using a 50 m interval, rather than the standard 200 m, is small: most of the expense in such a project would be the overheads in establishing a field party on the river. Moreover, because most sediment deposition appears to be over a large area in the lee of bar crests, rather than simply by forward advance of the crest, it should be clearly recognized that monitoring movement of bar crests by aerial photography would provide only a crude measure of transport volume.

6.2.3. After complete analysis of the results of Rec. #6.2.1, a pair of pool-riffle units, corresponding to a river length of about 15 km, should be selected on the lower Mackenzie. This should be surveyed annually for a period of at least 5 years.

It is possible that the work noted above could be done by CHS (or through subcontracts) if bathymetric work is to be done by them on the Mackenzie over a period of years. This would have the major advantage of reducing overheads. On the other hand, it would seem to be an excellent example of the kind of research mapping that should be done by the Water Resources Branch, utilizing its HYDAC and HYDRA facilities (Durette and Zrymiak, 1978; Durette, 1981). The annual field programme would be sufficiently short that the work could be done at high water allowing topographic changes over bar tops to be monitored. Data should be provided in digital form. The programme should last at least five years, though the important factor here is to ensure inclusion of years with widely different flow conditions.

'In the region downstream and upstream of Fort Good Hope, utilization of both existing and new charts would contribute greatly to determination of the bed material budgets in these areas.

6.4.1. CHS charts 6422-23 should be digitized and subjected to the same analysis as recommended in 6.2.1. This would provide estimates of the bed material load at the entrance to the Fort Good Hope trench.

Upstream of Fort Good Hope, estimation of the sandy bed material input of Mountain River is fraught with many difficulties: e.g. the bed material is mixed sand and gravel, not sand alone; e.g. morphometric analyses based on repeated aerial photography would require flights after every flood period, otherwise the loads would be drastically underestimated because of non-systematic changes in channel pattern; e.g. most of the Mountain River sand that becomes incorporated into the Mackenzie bed material load may, in fact, be wash load in the lower reaches of the Mountain River, not bed material load. The best method for its determination may well be a bed material budget for the general area as illustrated in Fig. 11. Assuming that inputs from Norman Wells and outputs to the Fort Good Hope trench are known, the difference between these two values represents primarily the input from the Mountain River, and the change in bed storage in two reaches of likely aggradation at the Hume Crossing shallows and the Axel Island flats.

6.4.2. Two new surveys should be initiated. One should be of parts of Charts 6419 and 6420, between km 965 and km 1014, this being the extremely gentle reach in the vicinity of Axel Island. The other should be the Hume Crossing shallows (km 1030 - km 1080) between Sans Sault and Ramparts Rapids. Data should be provided in digital form. The priority for these two surveys is very high.

In the longer term, attention should be directed to the feasibility of providing direct estimates of both suspended load (see Section 5) and bed material load from Mountain River by establishing a full sediment station near the mouth of Mountain River. On the other hand, it may be preferred to compute the Mountain River suspended load indirectly as well (See Section 5 (c)).

Upstream of Norman Wells, the combined Mackenzie-Liard bed material load could be determined by morphological analysis provided that a repeat survey of the stretch between km 390 and km 455 is made.

6.5.1. A new survey of Chart 6411 should be undertaken as soon as possible.

With this knowledge of the combined Mackenzie-Liard load, the additional loads of the North Nahanni and Root Rivers could then be determined by morphological analysis of the next stretch downstream (km 489 - km 511) and comparison with the km 390 - km 455 reach. Such analysis would also be useful in indicating the degree of any aggradation in this reach.

6.5.2. Existing sheets for CHS chart 6412 should be digitized between km 489 and km 511.

On the other hand, the shortness of this reach does lead to some concern about how accurate the morphological approach will be there. Downriver from km 511, the river steepens markedly (the Wrigley reach) and appears to be largly non-alluvial. This problem may, however, constitute a definite advantage. The apparent absence of large areas of sand on the bed in the Wrigley reach (according to the CHS charts) suggests an alternative strategy in computing the input of sediment from upstream to the sandy bed material load of the Mackenzie at Norman Wells. If the sand load downstream of km 511 has been converted to wash load, then a suspended sediment sampling programme at Wrigley, with grain size analysis, would provide the necessary information. In

effect this reach seems to provide an ideal opportunity to determine bed material loads by suspended sediment sampling at "contracted sections", long ago advocated by Colby (1957) in the USA. The town of Wrigley itself would provide an ideal base.

6.5.3. A detailed bed material sampling programme should be undertaken on the Mackenzie in the vicinity of Wrigley to verify that, indeed, sand deposits are minimal in this reach. If this is confirmed, a suspended sediment sampling station should be established in this area, and given high priority.

If extensive sand deposits are found on the bed near Wrigley, reliance will have to be placed on resurveys of km 489-km 511. It is true that another possible "contracted" reach exists: the even steeper gravel-bedded stretch of the Mackenzie downstream of the Redstone river. However this is not as accessible, and, furthermore, would include inputs from the Redstone and possibly the Keele, depending on the location. In that case it would merely constitute a check on the estimates for the Norman Wells reach, rather than attempting to partition the load at Norman Wells into its source areas. Establishment of a station at Wrigley would allow determination of the Redstone-Keele inputs through the difference between loads at Wrigley and Norman Wells.

In terms of inputs of gravel to the main river, the major reach of interest is the Redstone-Keele fan. It was noted earlier in (c) that aggradation appears to have created a hump in the long profile at the Redstone confluence; and it will seen in Section 7 that this may be a factor in navigation difficulties in this reach. Some attempt to determine medium term (10 years) rates of input of gravel in this reach is therefore warranted.

6.6. A bathymetric survey of the reach between km 705 and km 790 (comprising part of Chart 6415 and most of 6416) should be initiated. It is of relatively low priority, but could, in the right circumstances, yield invaluable information on gravel yields from west bank tributaries.

SUMMARY OF RECOMMENDATIONS

The recommendations made above deal primarily with the use of bathymetric charts to compute bed material loads. They involve a first stage in which existing charts should be analyzed to yield patterns of change in the bathymetry and estimates of loads through the reach. A second stage is envisaged in which

new surveys are undertaken on selected reaches. These are summarized in Table 11; they amount to about 275 km of river needing an immediate resurvey. A third stage is suggested for the key reach just upstream of the Lower Ramparts in which a 15 km reach is subjected to detailed survey on an annual basis for about 5 years.

In all surveys, it is highly desirable that they be done (a) at high water so that bar elevations are included and (b) in one, or at the most, two seasons, so that comparison of results from one reach to another is not complicated by differences in hydraulic conditions during the time periods between surveys. To some extent these two goals are incompatible: long field seasons will involve low water conditions. It is therefore important that echo-sounding is complemented by ground surveys of islands and bars above water.

As Table 11 indicates, no surveys of the Mackenzie River downstream of Fort Simpson have been undertaken by CHS since 1979. In the mid-80's, however, it had been hoped to undertake a major resurvey of the river using funds sponsored by NOGAP. A three year period of funding by NOGAP was, in fact, used to undertake new surveys between km 0 and km 208. The work was done by Terra Surveys Ltd of Sidney, B.C., and involved the development of new procedures for the direct transfer of echo-sounding records directly to digital format on tape. The report by Terra Surveys Ltd made the comment that "The CHS program to resurvey the Mackenzie was well-received by users of the Mackenzie charts". Unfortunately, further funding from NOGAP has not been forthcoming.

While competition for NOGAP funding is obviously keen, it would seem that a stronger case could be put forward for CHS work in charting the Mackenzie. In discussions with senior CHS staff, for instance, the potential use of CHS charts in computing bed material discharge, delineating areas of aggradation, etc. had, understandably, not been appreciated. Thus the overall value of the CHS programme to the scientific, engineering and environmental communities has not been recognized. NOGAP is presently funding many other projects related to the Mackenzie, and yet some of these will be of dubious value until a better understanding of the sediment yield of the Mackenzie is attained.

It would seem sensible for the Water Resources Branch to initiate a new attempt to lobby NOGAP and others regarding these general points, and, in particular, emphasize the major role that can be played by the Canadian Hydrographic Service through its updating of Mackenzie River charts. Alternatively, given that bed material movement is already part of the domain of the Water Resources Branch, and given that conventional methods of sampling are costly and inaccurate, it may be more appropriate to seek funds for the expansion of the technical unit within the Water Resources Branch that deals with bathymetric surveys.

7. NAVIGATION PROBLEMS ON THE MACKENZIE RIVER

(a) ISSUES

Certain sites on the Mackenzie already present problems to barge traffic and limit the annual freight volume. Though traffic is estimated to decrease to 1990, due to a decrease in oil exploration work in the Delta and Beaufort Sea areas, an increase of more than 50% is expected by 1994 due to the start of construction associated with oil development, and almost 300% by 1998 at the time of natural gas related construction. After these peaks, traffic is expected to drop back to levels that are still 50% higher than today (Acres, 1987).

Present navigation problems on the Mackenzie are likely to be exacerbated if the Liard is dammed for hydro-electric power development. BC Hydro (1984) has outlined changes in flow regime associated with Scheme 2 (the Devil's Gorge - Beavercrow option): summer flows on the Mackenzie would be reduced by approximately 15 percent on average. A more detailed analysis for the lower Liard near its mouth indicates that "summer discharge under the regulated flow regime would be reduced approximately 37%, with minimum flows during the open water period remaining much the same" (p. 4-32). The lack of change in minimum flows arises because minimum flows occur at the end of the open-water season, by which time the effect of regulation is negligible. (Public Works Canada (1976), for example, used end-of-season dates of Oct 22 at Fort Simpson and Oct 12 at Fort Good Hope.)

Notwithstanding these observations, it is clear that damming of the Liard would result in an accentuation of low stages during the navigation season, and, in dry years, this could prove a further impediment to navigation. It should be noted that Acres (1987) did not address this problem on the grounds that the Liard River hydro-electric project proposed by BC Hydro is very unlikely to proceed within the time frame utilized by their study. A similar comment could be made regarding transfers of water out of the Mackenzie basin: they loom as a distinct possibility in the future, and may have adverse effects on navigation, but they seem to be beyond the time frame of the study by Acres and of this report.

Most of the problem areas on the Mackenzie are not related to bed material accumulation; they are generally in "rapids" areas, primarily upstream of Fort Simpson. There are, however, exceptions to this statement. Dredges operated by Public Works Canada have removed, on average, slightly more than 40,000 cubic metres of bed sediment per year over the last 23 years during routine maintenance dredging of some problem sites. The estimated cost of maintenance dredging in the years ahead is in the region of $1 million to $4 million, but is uncertain due to the difficulty of predicting rates of infill. The Canadian Coast Guard (which took over the marine program from Public Works in

1982) identifies this issue of rapidity of infill in potential dredge cuts as one of primary importance on the Mackenzie (Isfeld, pers. comm., 1987).

Another issue confronting the Coast Guard is the instability of channel bathymetry arising from bed material movement. They comment that "it would be useful to have a basic understanding of the meander pattern of the thalweg as it relates to the stability of the marked navigation channel. In other words, we would like to know where relatively rapid change might be expected which could adversely affect the towing channels." (Isfeld, pers. comm. 1987).

From a different standpoint, the effect on fish of increased wash load concentrations, and associated contaminants, that might temporarily result from dredging activity has been raised as an issue by Indian and Northern Affairs.

(b) INFORMATION NEEDS

The basic information needed to address the issues raised by the Coast Guard will only emerge when a proper understanding of the movement of bed material along the Mackenzie channel bed, especially as it varies along the course of the river, has been acquired. In particular, information bearing on the following points must be gathered: (i) the major processes of bed material transport, shoaling and instability of the bed; (ii) the source of bed material that accumulates in specific areas and the reasons for accumulation of sediment there; and (iii) the rates of supply of bed material to these problem areas. The last of these is essential in attempting to estimate the frequency of maintainance dredging.

Clearly, much of this information would emerge with implementation of the recommendations in Section 6, which deals with acquisition of data on rates of bed material transport in different reaches of the Mackenzie. Of course, local circumstances will also be important and necessitate more detailed information in some areas. Nonetheless, it should be absolutely clear that the logical approach here is, firstly, to understand the behaviour of the river at the reach level, and then, and only then, focus on site-specific circumstances.

As far as impacts of dredging on fish are concerned, the data requirements are threefold: (i) a sound knowledge of the movements of fish, by species, at different times of the year in relation to proposed dredging areas; (ii) data on the suspended sediment plumes that result from dredging: concentration of sediment and pollutants (and their duration) as a function of distance downstream; and (iii) the threshold levels of turbidity, for different durations and different suspended particulates, as they vary with fish species. Of these, the first and third belong to the domain of fisheries research, and only the second to that of sediment investigations.

(c) ADEQUACY OF EXISTING INFORMATION

Based on the comments made in Section 6, it should be evident that virtually no data exist at present to address the issues raised by the Coast Guard. The same point was made by Acres (1987), at the conclusion of their report. They emphasized that: "as information on existing bed loads is virtually non-existent, a survey should be undertaken to provide a basis for determining potential infill rates at the twenty-six priority dredging sites".

Before making specific recommendations in this report, it would seem worthwhile considering each of the sediment-controlled problem areas, and noting, in each case, how the recommendations of Section 6 would contribute to an understanding of the river's behaviour at those sites. Though the general reader may find these specific site descriptions of little immediate interest (and may wish to move directly to item (d)), the fundamental importance to these navigation issues of a proper scientific understanding of bed material transport along the Mackenzie (as outlined in Section 6) will become very apparent.

Most of the navigation difficulties on the Mackenzie occur in shallow, fast flowing, non-alluvial areas. Most of these (and shallow lacustrine tracts) occur upstream of Fort Simpson where bed material transport is assumed to be very small. Between Fort Simpson and Point Separation, the only problem sites identified by Acres (1987) are in downstream sequence: McGern Island; near Blackwater River; above Saline River; Saline Island; below Smith Creek; Norman Wells (harbour access only); Rader Island; Sans Sault Rapids; Hume River Crossing; and the Ramparts Rapids. Added to these should be Camsell Bend, Barrel Crossing and others, according to the Canadian Coast Guard and the Northern Transportation Company Limited (NTCL). Most of these problem areas reflect difficulties arising from mobile bed material.

i. Webber (pers. comm.) reports problems due to intermittently shallow conditions around Cameron Point (km 425) and Camsell Bend (km 460), part of Reach 7. The possibility of aggradation in this reach associated with inputs from the North Nahanni has been noted. A preliminary assessment of this problem would be afforded by implementation of Recommendation 6.5.1.

ii. The area around McGern Island (km 491-520: Charts 6412/13) is plauged by sand bars and shallow rock areas. The area is the downstream tract of Reach 7. The problems here may also be related to the North Nahanni River. Implementation of Recommendation 6.5.2 would at least provide some insight into processes operating between km 489 and km 511.

iii. The problem area just downstream of Blackwater River (km 665-670: Chart 6415) corresponds to the marked step down in the long profile noted at the end of the Wrigley (8) reach (Fig. 4a). The bed here is gravel-covered, the channel widens appreciably at a sharp bend, and the low water profile drops dramatically at a gradient of 60 m/100 km over a distance of about 3.5 km. Depth reduces accordingly, and velocities increase. The cause of this stepdown is not known, but it seems to be a purely local phenomenon. The reach upstream is not considered to transport large quantities of gravel to the site.

iv. The reach above Saline and Redstone Rivers (km 707-712: Chart 6415) is a shallow sand-bed area in which the navigation channel hugs the right bank, even though the thalweg swings to the left bank and then back across the river. This does not mean, however, that navigation difficulties stem from bad alignment of the ship channel. Though the area is part of the relatively steep Reach 9 (Fig. 4a), it is immediately upstream of the Redstone-Keele gravel fan (Reach 10), and its slope is only 18 m per 100 km, much flatter than both upstream and downstream. It is possible that local aggradation at the mouth of the Redstone has raised local base level for the Mackenzie immediately upstream, leading to deposition of sand. Implementation of Recommendation 6.6, followed by repeat surveys when appropriate, and extended slightly upstream to allow examination of backwater effects, would assist in the analysis of this problem area.

v. The problem areas close to Saline Island (km 722-726: Chart 6415) and Smith Creek occur in Reach 10, the gravel fan of the Redstone and Keele rivers. The exact problems in these areas are not known. Implementation of Recommendation 6.6 would again provide a basis for further investigation.

vi. Major dredging is planned to improve access to the Government Dock at Norman Wells from the navigation channel, accompanying the expansion of the activities of Esso Resources Canada Limited. Acres (1987) predicts a high infill rate here. However, sedimentation may be more from suspended load than bed load because the right side of the river here (to a large extent being water from Great Bear River) has a non-alluvial (till and glaciolacustrine clay) bed. Suspended sediment loads should also be less on this side of the river because of the dilution of the Mackenzie load by Great Bear water. Analysis of the matter is complicated by the recent artificial construction of islands near the downstream end of the

proposed channel. The problem of future infill is primarily a local one and will require a detailed investigation of both mobile sediment on the channel bed upstream and the suspended sediment load in this part of the river. Public Works Canada (1976) considered this to be a relatively high maintenance site "as the channel alignnment must be made at an angle to the flow, and high steep wave action can occur from time to time"; they estimated maintenance dredging of 143,400 cubic yards place measurement per annum.

vii. The Hume River Crossing corresponds to the wide, shallow, sand-bedded 50-km Reach 14, downstream of Sans Sault Rapids. The problem area itself is given by Acres (1987) as between km 1030 and km 1033, but this is not the location of the mouth of the Hume River. On the other hand, this designated 3 km area does correspond to a previously documented problem zone at the start of Reach 14 (Public Works Canada, 1976: Priority Area 25). Acres (1987) notes that a grounding occurred here in 1985. The Hume River mouth (km 1065) corresponds to Priority Area 26 of the PWC 1976 report, and is reported as a serious problem due to channel shifting by NTCL (Woldmo, 1988, pers. comm.).

The problems in Area 25 (1976) again seem to be local ones arising from the fact that the navigation channel does not follow the main thalweg. The thalweg actually splits around Hardie and; the navigation route follows the left side of the island, whereas the main thalweg takes the right hand route before crossing over to the left bank in the lee of Hardie Island. Although both thalwegs involve shallow crossings to the left bank, the right thalweg appears to be better, based on the 1983 chart. However, it is not difficult to imagine that the relative advantage of the two thalweg routes varies from year to year.

The problems at this one small area would seem to be indicative of more widespread shoaling problems throughout Reach 14. Though Mackay and Mathews (1973) believed that longterm degradation was still continuing upstream of the Ramparts, this is not completely consistent with the appearance of Reach 14. Aggradation, at least in the short term, may be occurring. As noted in Section 6, this general area is a crucial one in the sediment budget of the Mackenzie. Implementation of Recommendation 6.4.2 would assist in analysis of the more practical problems of navigation in the Hume Crossing shallows.

viii. Problems have also been reported at Barrel Crossing (km 1350) at the end of Reach 17 (Woldmo,

1987, pers. comm) due to the shallowness of the entire channel and instability in the thalweg location.

(d) RECOMMENDATIONS

Some of the problem areas noted above are controlled by local conditions and require a detailed analysis of where the sediment that forms the shoals originates and how quickly it is supplied to the shoal area. In general, this is probably beyond the domain of the Water Resources Branch. Monitoring would have to be done at a very detailed scale. Each location would require investigation by an expert in bed sediment movement and river hydraulics. This is a matter for the Coast Guard, Public Works Canada, and their consultants.

The one site in which the Water Resources Branch should probably take an active role at the local scale is Norman Wells. The Water Survey of Canada already operates a hydrometric station here (10KA001). To date the only suspended sediment data at this station are for 1973, with seven concentration values (maximum 513 mg/L at 20,500 cms). On four of the five sampling occasions more than two-thirds of the sample was silt and clay. Galay (1978, p. 60), on the other hand, claimed that "natural suspended sediment concentrations range from 300 mg/L to 8,000 mg/L". In neither case is the location of the sampling points known relative to the proposed channel.

It has already been recommended in Sections 4 and 5 that a full suspended sediment monitoring programme be established at Norman Wells, and, given this, it would seem appropriate to undertake that programme in such a way that it also provides data relevant to the dredging issue at this site.

7. The Water Resources Branch should seek funding from all concerned parties to reestablish the sediment monitoring programme at Norman Wells, with special attention being placed on the cross-channel variance in concentration and grain size, and on loads in the vicinity of the proposed channel.

This work would need to be supplemented by a study of current speeds and directions upstream of the cut, and a survey of bed material, in order to establish the likely bed load infill rate. (See also Section 10.) It should be noted that surface water speeds and directions were mapped between Norman Wells and Sans Sault Rapids in the early 1980's (Sikstrom, 1988, pers. comm.), but whether data are availble immediately upstream of Norman Wells is uncertain.

Apart from this specific site, it should be evident that most of the problem areas would benefit from far more information than is currently available on the general pattern of aggradation in certain reaches, the rates of bed material transport through those reaches, and the rates of migration of bedforms (and thalweg). Implementation of the recommendations in Section 6 is a vital first step in this regard, especially in view of the increase in barge traffic predicted in the years ahead.

Environmental impacts of dredging have already been considered in some detail by Renewable Resources Consulting Services Ltd (1978), and no further study seems warranted at this time. Monitoring of suspended sediment for hydrocarbons (Rec. #4.1.2) and for metals (Rec. #4.2), upstream of Fort Simpson (10GC004), would maintain an inspection procedure on that part of the river which will be subjected to most navigation dredging.

8. MAGNITUDE OF SCOUR AND FILL IN SAND BED REACHES

(a) ISSUES

Erosion of the channel boundary, whether it be short-term scour of the bed, or more progressive undercutting of channel banks, looms as a rather significant concern at specific sites that may be proposed for pipeline crossings. Exposure of a buried pipeline by removal of overlying bed sediment or undercutting of bank material could lead to rupture of the line with disastrous consequences. Church (1971), addressing this issue in a report for Mackenzie Valley Pipe Line Research Ltd, emphasized the need for observations on seasonal scour and fill, particularly in connection with the possibility of increased bed scour under winter ice at times of increased discharge.

The existing Interprovincial Pipeline from Norman Wells to Zama Lake crosses the Mackenzie just upstream of the Liard confluence. Polar Gas has submitted an Application to the National Energy Board and to the Department of Indian and Northern Development to build a gas pipeline along the north east side of the Mackenzie Valley which would cross the river at essentially the same site (Naylors Landing) (Kaustinen, 1987, pers. comm.). Townsend (1987, pers. comm.) indicates that preliminary route selections for a pipeline for Gulf Canada Resources Ltd also favour this site, though technical level studies are not likely to be initiated until late this year at the earliest.

The area of Naylors Landing is just downstream of the Green Island Rapids. It is straight and narrow, with little obvious morphological evidence for rapid bank scour. The narrowing of the channel corresponds to some overdeepening of the bed in this reach, but the bed material is reported as gravel and boulders over till.

The Polar Gas line is planned to extend from the Mackenzie Delta to Edson, Alberta. It involves a crossing of the Mackenzie East Channel at Swimming Point. The crossing is just downstream of the Gulf Oil Base Camp, located on the inside bank of a rather sharp meander bend.

Gulf Canada's plans for transmission from Amauligak are still preliminary. One route would come directly to land at Toker Point (east of the Delta) and thence overland to Inuvik and the south. A second possibility is to have landfall at North Point on Richards Island, crossing the East Channel in the vicinity of Swimming Point also.

At first sight there would seem to be some concern about the Swimming Point crossing. As just noted, it coincides with a sharp meander bed which would be expected to be liable to bank

scour. The Application by Polar Gas notes that the site was previously investigated for the Canadian Arctic Gas Study Ltd in 1972-74, and states that there has been no significant change in bank locations for many years (this is based on a comparison of aerial photographs taken in 1950 and 1972: Neill, 1988, pers. comm.). Apart from the worry of progressive bank erosion here, there must also be some concern regarding short-term scour. The site coincides with an abrupt narrowing of the channel as it leaves the wide bend zone.

Maximum design scour at the site was previously estimated as 5 m below the lowest part of the cross section, according to the Application. Bed material is reported as unfrozen sand and occupies a scour hole slightly more than 12 m below low water datum according to CHS chart 6430. What the stability of these scour holes is during floods, i.e. how deeply they scour before refilling back to the 'normal' depth is not known, and is also therefore of concern.

(b) INFORMATION NEEDS

In terms of bank stability, each crossing site must be examined in terms of its own peculiarities. Analysis of the morphology, sedimentology and vegetation patterns provides some indication of long-term bank stability. Replicate aerial photographs taken over periods of time will provide more quantitative information on rates of channel shifting and bank scour.

Assessing bed scour is more difficult. Thalwegs (the downstream line following the deepest part of the channel) migrate with bedforms downstream. In the medium term, therefore, the maximum scour at a point (due to thalweg migration) could be assessed by examination of the existing channel bathymetry. The crucial issue, however, is short-term scour in which the thalweg becomes overdeepened during short-lived extreme flow conditions, before sediment settles back on the bed with infilling to pre-scour levels.

(c) ADEQUACY OF EXISTING INFORMATION

No comment can be made on the adequacy of information at specific sites, as this has not been examined as part of this study. The nature of the bed and banks at both sites has, however, been investigated by other consultants as part of the original study by the companies involved.

How representative the rates of bank scour are at Swimming Point, in terms of future conditions at this site, is obviously a question of some importance. Neill (1988, pers. comm.), representing Northwest Hydraulic Consultants, who were engaged by Polar Gas in connection with its Application, reports that assessment of this site was based on field reconnaissance only,

the philosophy being that detailed studies would proceed as design studies if the application received a favourable response.

Short-term bed scour in unfrozen sand is well-documented in many other meandering rivers, and data are available to provide estimates of scour in relation to bend curvature, bed material and flow depth and intensity. Presumably these data were also examined in assessing the maximum design scour, though it certainly would have been informative to have had the magnitude of scour and fill at the Swimming Point site monitored during the years since the 1972-74 study. No work has apparently been done on this topic at that site since then (Neill, 1988, pers. comm.).

The major problem here, however, is that little is known about the magnitude of scour and fill under ice, especially during periods of rising flow, and during ice jam conditions. Petryk (1985), in a casebook on ice jams prepared for the National Research Council of Canada, briefly mentions study of an ice jam release on the Mackenzie River near Arctic Red River in which "high velocities were observed", but no further details were given. The field observations are documented in reports by T. Blench & Associates to Northern Engineering Services for the Canadian Arctic Gas study. The reports are available in the library of Northwest Hydraulic Consultants in Edmonton.

(d) RECOMMENDATIONS

Short-term scour, especially under winter ice or during ice jams, is difficult to monitor. There appears to be no simple technique available for measuring short-term scour in rivers with depths as great as those in parts of the Mackenzie thalweg. Yet clearly this topic is of major concern.

> 8.1. Research funding be sought for methods of measuring short-term thalweg scour and fill, particularly under ice breakup conditions. An appropriate organization to conduct this work would be the National Hydrology Research Institute. Its practical significance should be obvious to any granting agency.

A logical site for this work is the planned crossing at Swimming Point. Though the purpose of the research would be to improve our knowledge, generally, on this topic, the actual severity of scour will be highly site-specific. For this reason, and bearing in mind the high costs involved, it could only be justified in relation to probable project locations. Though isolated, the Gulf Oil Base Camp might serve as a field station.

Irrespective of the findings of the research suggested above, the ultimate fate of any pipeline crossing will, to a large extent, depend upon where, along the Mackenzie, it is sited. Some areas are in relatively immobile bed material, and do not constitute a worry. Other areas involve sediment that is mobile to depths of at least 20 m below low water datum, and are potentially hazardous. It is assumed that proposals for pipeline crossings are given close scrutiny by appropriate Government agencies.

9. INFLUENCE OF SHOALING ON THE LOCATION OF ICE JAMMING

(a) ISSUES

Ice jams constitute an issue of some importance on the Mackenzie river. Severe flooding at Fort Simpson in 1963 and 1972, and at Fort Norman in 1964 and 1972, resulted from ice jams. Kriwoken (1983) has provided a detailed review of past flood events in seven communities in the lower Mackenzie system, almost all of them caused by ice jams during spring breakup.

Work by the National Hydrology Research Institute (NHRI) has recently indicated a possible connection between sites of shoals and locations of the river that are particularly liable to ice jams during breakup (Prowse, 1987. pers. comm.). MacKay and Mackay (1973) presented data that implied a similar relationship. A better understanding of the role played by shoals in this process might allow remedial measures to be taken to prevent ice jams, or at least improve prediction of such events.

In order to appreciate the role of shoals in this problem, it is worthwhile providing a brief summary of the jamming process. Usually, the ice cover along a south-to-north flowing river such as the Mackenzie will disintegrate first in the upstream reaches; the front between fragmented ice and the intact ice cover will then advance downstream. The front advances as the intact ice becomes fractured into small-diameter floes under the pressure of the upstream mass. Prowse (1986), for example, noted that in 1983, on the Liard, the downstream progression of this breakup front averaged over 5 metres per second along the 18 km study reach, substantially faster than the flow of water itself. When particularly strong intact ice is encountered, or the crushing forces decrease, the advance of the breakup front will slow, and even stall, and may then become the toe of an ice jam.

A sudden change in river morphology from deep fast flow to a downstream area that is wider and slower is a favoured site for such stalling. Ice pressures from the more slowly moving flow are reduced by being dissipated over a greater width of front. The probability of stall is further increased if the downstream depths are sufficiently shallow that, over much of the channel width, river ice penetrates into the channel bed. Even in deep flows, however, the breakup front may stall if especially strong or thick ice is encountered.

Stalling of the breakup front does not necessarily cause an ice jam. The key factor here is whether the congestion of fragmented ice reduces the cross-sectional area of flow for the water (and increases the roughness of the water boundary), thereby decreasing the velocity, or whether the floes upstream of the front simply repack into a relatively smooth floating ice cover again. To a large extent, this is conditioned by the water

velocity. At high velocities, ice floes can be swept under the cover of an intact ice sheet and deposited in a lower-velocity section downstream, forming a hanging dam. Water will then back up, because of the reduced area for flow (and the reduced velocity due to the roughening of the water-ice interface), until the cross-sectional area is increased sufficiently (by the floating of the ice-sheet to higher levels) that continuity of water flow is renewed, or breakup occurs.

Stalling is, perhaps, more likely to be accompanied by ice jamming in shallow areas, however, because grounding of large ice blocks is more frequent; this may lead to miniature jams and surges that will carry the ice debris under the sheet of intact ice. Jamming is also favoured in areas of flow convergence which force fragmented ice beneath the surface. Such conditions of convergence (and divergence) are characteristic of many shoaled areas.

Examination of locations of high driftwood levels associated with ice jamming on the Mackenzie by MacKay and Mackay (1973) indicated many areas in which severe jams occurred (driftwood more than 10 m above June 30, 1970 water level). Of 11 sites downstream of the Liard, only two seem unrelated to shoaling, indicating how important this aspect of the process is. The problem is not restricted to the Mackenzie. In the 1986 IAHR Ice Symposium, Beltaos and Wong (1986) commented as follows:

> "Experience suggests that ice jams are often grounded, usually near their downstream end or 'toe'. Whether and to what extent a jam grounds are important questions in assessing flooding potential, stability and release, but little is known about grounded jams."

(b) <u>INFORMATION NEEDS</u>

There are two major requirements in the context of this problem. One is a much better understanding of the mechanisms involved in ice jam formation, with a clear distinction between stalling and jamming. Key questions to be addressed here would be: How strong must the intact ice be to cause a stall? How much grounded or bottomfast ice is necessary to induce a stall? What causes the actual jamming: normal two-dimensional water flow, surges due to mini-jams, under-ice transport of ice debris due to flow convergence, etc.?

The other requirement, subsequent upon the former, is monitoring of key variables at problem sites in order to assess whether chronic ice-jam flooding can be alleviated (e.g. by dredging) or predicted well in advance. Though a monitoring programme is best deferred until the ice jam process is better understood, it makes sense, nonetheless, to undertake the basic research into ice-jamming mechanisms in the same river reaches that will be later subjected to routine monitoring.

(c) ADEQUACY OF EXISTING INFORMATION

Substantial research was undertaken on patterns of ice jamming in the Mackenzie Delta distributaries in the 1960's (MacKay, 1965, 1966), but did not address the issues identified here as affecting the main stem.

Research into ice jam development by NHRI in recent years has been concentrated on the Liard River at its confluence with the Mackenzie. Prowse (1984) provides a particularly good overview. Given the role of the Liard breakup in starting ice clearance on the Mackenzie itself, this emphasis on the Liard is understandable. On the other hand this type of ice jam, a tributary or "estuary" type jam, though similar to ice jams in the Mackenzie Delta, and elsewhere in Canada, does not seem to be representative of most jams along the mainstem river.

Elsewhere on the Mackenzie, one obvious other area of practical concern is Fort Norman where flooding is also a problem. According to CHS Chart 6417, the thalweg shoals rapidly in this area from 11 m below low water datum to less than 4 metres. Most of the main channel on the right side of Windy Island is above the low water datum, and spot soundings near the narrow thalweg zone are only 2.8 m and 3.2 m. The changing spatial extent, from one winter to another, of bottomfast ice in the Mackenzie opposite Fort Norman, and its relationship to the degree of ice jamming, would seem to be a topic worth investigating. Certainly, it would appear to be more representative of other ice jam locations on the Mackenzie than is the Liard site.

Conditions at this site are briefly mentioned in a joint study by Esso Resources Canada Ltd and the University of Alberta (Rivard et al., 1984), but most of that report dealt with ice jamming downstream at Norman Wells, where the channel narrows and the thalweg itself is further confined by an island on the west side.

Kamphuis and Moir (1983) have documented ice jam locations on the main stem between Fort Simpson and Norman Wells, but to date there does not appear to have been any detailed examination of ice jam formation on the main stem in relation to shoaling.

(d) RECOMMENDATIONS

The few detailed analyses of ice jamming on the Mackenzie seem to be primarily in relation to prediction of water level profiles in floating ice jams. There is little, if any, detailed information on the role of shoaling on the development of grounded ice jams, notwithstanding the strong association of shoaling and ice jam locations along the Mackenzie.

9.1 The cost/benefit value of a study of ice jamming near Fort Norman be considered by NHRI. Identification of the exact role of shoaling in jams in shallow areas might provide not only a means of predicting the probability of ice jamming, but permit some assessment of whether dredging of critical areas could actually alleviate the problem. (See also Rec. #10.2 in connection with Norman Wells.)

Whereas studies such as current work at Fort Simpson, and suggested work at Fort Norman, allow the identification of processes at work in ice jamming, it would seem worthwhile also to assess the overall downstream pattern of ice jamming along the Mackenzie River, on an annual basis. This would establish the consistency of that pattern, and any correspondence with the locations identified by MacKay and MacKay (1973), as part of the general problem of bed material movement down the Mackenzie.

The location of ice jamming along the Mackenzie has been reviewed by NHRI on several occasions (Prowse, 1988, pers. comm). Nonetheless, this kind of "global" monitoring on an annual basis should be maintained as a longterm goal. Unfortunately, at the present time, it is difficult to implement using satellite imagery: resolution is adequate, but image repeats are, at best, of the order of 11 times in 26 days, and the cost is prohibitive. Once imagery becomes less expensive, and image repeats more frequent, however, it should be utilized to record the breakup of the Mackenzie annually. Such information would be invaluable in the longterm planning of the Mackenzie corridor. In the present context, it would allow continuing reassessment of the changing pattern of ice jamming in relation to changing locations of shoaling.

10. ENLARGEMENT OF ARTIFICIAL ISLANDS AT NORMAN WELLS

(a) ISSUES

As part of the Norman Wells oilfield expansion project, Esso Resources Canada constructed six artificial islands in the channel of the Mackenzie, by dredging sand and gravel from the river bed. The locations of the islands are shown in Fig. 12, taken from CHS Chart 6418. Two are north of the navigation channel, four are south of it. The two on the north side lie upstream of the proposed new channel to the Government Dock at Norman Wells.

Since their construction in 1983, the islands have apparently continued to grow (Sherstone, 1987, pers. comm.) and several scientists at Indian and Northern Affairs Canada commented upon this as a possible, though somewhat poorly defined, environmental concern. It would certainly seem that some assessment of what is going on would be in order, not only in relation to Section 7 (proposed dredging to Norman Wells) and Section 9 (possible effects on ice-jamming), but in the more general context of understanding bed load movement processes in this part of the Mackenzie. Islands play a major role in bed material transport, often trapping sand at the upstream end and sometimes losing it at the downstream end. Any island which is protected from bank scour may thus be anticipated to enlarge and become a trap for bed sediment (as well as suspended sediment) from upstream.

A further aspect of this island construction also needs to be considered: slightly over a million cubic metres of alluvial sand and gravel were dredged from the bed to form these islands. Another three-quarters of a million cubic metres were removed for other purposes, yielding a dredging total of about 1.8 million cubic metres (EBA, 1987). The impacts of this removal of (presumably) mobile bed material from the live channel on normal bed material transport through the reach would have been worthy of study. The matter is considered in Section 11 as part of the general issue of mining of river bed sediment.

(b) INFORMATION NEEDS

In terms of monitoring the rate of growth of these islands, an annual programme of vertical aerial photography, taken at a constant water stage on the Norman Wells datum, is required.

It would have to be supplemented by above-water levelling to determine amounts of vertical accretion, and bathymetric surveys at the time of photography to identify underwater changes, especially effects on the bathymetry of the channel between Goose Island and Bear Island.

Sampling of bed material in identified areas of accretion would permit interpretation of the mode of transport of this sediment prior to deposition: bed load versus suspended load; wash load versus bed material load.

Monitoring of ice breakup in the area is needed to provide a record of any changes in the propensity for ice jamming at this site in relation to the changing channel bathymetry.

(c) ADEQUACY OF EXISTING INFORMATION

The possible effects of the islands on channel bathymetry (and pattern) and ice jamming were previously considered by Northwest Hydraulics Consultants Ltd. (1979).

In terms of channel bathymetry, Northwest Hydraulic Consultants concluded that the two "lines" of islands would effectively reduce the cross-sectional area of flow in the area by about 10%, and that, to maintain a "regime" condition, sandy parts of the bed would be scoured to restore the original cross-sectional area. Little scour was predicted on the north side of the navigation channel (being "gravel and weathered bedrock"); most of it was predicted to occur in the thalweg itself (possibly amounting to 2 m or so locally) and on the south side of the channel. Progresive erosion of sand banks on the Norman Wells side of Goose Island was predicted. This would represent a contrast to conditions between 1950 and 1972 (inferred from aerial photographs): during that time, Goose Island appeared to shift towards the Norman Wells bank. Based on "regime theory", however, they regarded the present channel as somewhat oversize, so that the full degree of these adjustments might not take place.

In the relation to ice jamming, these consultants concluded that the changes would be far too minor, relative to the size of the river channel, to trigger formation of a dry ice jam, but that floating jams might become more severe. Specifically they remarked: "It seems possible to envisage a situation whereby, under worst ice conditions, high water levels upstream from Bear Island might be raised a few metres above the record high conditions of 1974."

These last conclusions were based on the fact that typical break-up velocity at Norman Wells (inferred from values of discharge and stage) was believed by them to be close to the critical value above which ice floes will just be carried under a cover, if sheets are keyed to form a surface obstruction, and that, while keying does not appear to be a serious problem under natural conditions, large sheets might occasionally key between some of the artificial islands.

(d) RECOMMENDATIONS

Apart from the possibility of increased ice-jamming, no major ramifications have been identified arising from the growth of these artificial islands. Nonetheless, an opportunity is clearly presented for an experimental study of the effects of obstacles on bed material transport, one which in relation to possible effects on the proposed channel cut to Norman Wells, and in terms of the future stability of the passage between Goose and Bear Islands, might produce observations of practical value to organizations based in Norman Wells.

Certainly the cost of providing routine aerial surveys of the nature of island growth is minimal, and given the previous recommendations (#4.1.2; #5.3; #7) to start a sediment sampling programme at Norman Wells, the opportunity would seem to exist for the Water Resources Branch and Esso Resources to collaborate in this respect. Any sediment station at Norman Wells will have to determine the strong cross-sectional variance in bed material and sediment loadings (because of the dominance of Great Bear River water on the north side of the channel). As already noted in Section 7, this cross sectional survey will also aid in estimating maintenance dredging of the channel cut to Norman Wells; the point being made here is that it could also be usefully linked with the programme to monitor the growth of the artificial islands.

10.1. A program of annual vertical aerial photography, at constant low-water stage, and related surveys, should be implemented with the purpose of monitoring the enlargement of these islands.

It would be appropriate for a government agency such as the National Hydrology Research Institute to administer the programme and coordinate it with the Water Resource Branch's sediment monitoring programme. Esso Resources Canada has, in fact, already done some bathymetric monitoring between 1983 and 1986; but no details have been seen, nor are the terms of reference of the work known. It is expected that Esso would participate in the programme suggested, and it would certainly be logical for local personnel to undertake the surveys. An additional advantage of having NHRI coordinate the programme is that the work relates closely to the proposed ice studies (discussed below) which NHRI would logically undertake in collaboration with Esso.

Investigation of water levels at Norman Wells associated with ice jamming has already been undertaken by Esso Resources Ltd in conjunction with the University of Alberta, as noted previously. In view of NHRI's extensive experience in monitoring

ice jams on the Mackenzie (and especially in view of the remarks in the previous paragraph), it would seem appropriate that NHRI also become involved in these investigations. In particular, it should consider developing at least a nominal monitoring programme for ice breakup at Norman Wells. This, together with monitoring of channel bed changes, would provide, over the long term, the opportunity to assess the impact of systematic bed changes on the propensity for ice jamming.

10.2 A basic programme of research into ice jamming processes and an annual monitoring of ice jams should be established in the Norman Wells reach, conducted in concert with the studies of Rec. #10.1.

11. MINING OF RIVERBED SAND AND GRAVEL RESOURCES

(a) ISSUES

Indian and Northern Affairs in Ottawa raised this issue in terms of potential environmental consequences. Whether or not it is serious will depend upon volumes involved, rates of extraction and sites.

With increasing development of the Mackenzie corridor in the next decade, granular borrow material will be needed in large amounts. Williams (1986), in particular, has highlighted the technical problems of construction in general, and especially pipeline operation, in areas of discontinuous permafrost such as the Mackenzie Valley. Thaw of frozen ground by warm pipelines and frost-heave associated with cold pipes are still unsolved problems. He describes the case of the Norman Wells-Zama Lake oil pipeline, and notes that, after only a year in operation, tens of kilometres of its length were affected by an artificial shallow "thermokarst" due to thaw. Maintenance of the line involves filling the subsidences. In terms of cold (gas) pipelines and highway construction, vast amounts of granular material are needed to prevent frost-heaving. The major unknown here is the quantity of sand and gravel that will be needed.

EBA (1987), for example, reports that plans by Gulf Canada Ltd for a 20"-24" pipeline along the full length of the Mackenzie Valley specified approximately 2 million cubic metres of granular material. In contrast, an analysis of the Canadian Arctic Gas Pipeline Limited (CAGPL) proposal for a 48" pipeline, undertaken by EBA (1980) for Polar Gas between Jean Marie River (km 270) and Thunder River (km 1300), indicated 11 million cubic metres of borrow material. This is almost twenty times the annual bed material yield of the Mackenzie at Norman Wells computed by Church et al. (1986) for 1950-1971! To be sure, not all of this would be obtained from the river bed (but see below); the comparison does give some indication, however, of the possible scale of demand for granular material.

Sneddon (1988, pers. comm.) emphasized that the high figure for the CAGPL line was based on a large diameter pipe and on mid-1970's design, and that recent planning and preliminary design for a smaller diameter pipe suggest that much lower borrow volumes ("possibly as little as 2 million cubic metres") will be required for the presently proposed hydrocarbon transportation scenario. Again, the uncertainties are clearly indicated.

There is also still some debate as to whether pipeline construction demands for granular material have really decreased appreciably in the last decade in relation to the ever-present problem of frost heave. Williams (1986), for example, believes that little progress has been made in this regard. The implication is that development of the Mackenzie corridor will

involve vast quantities of sand and gravel; and the river bed itself is an obvious source.

It should not necessarily be construed that mining of large quantities of granular material from the river bed would be detrimental to the river system. In some situations it may be advantageous: much depends on the circumstances involved. For example, on some gravel-bed rivers in New Zealand, in areas of chronic aggradation of bed material, commercial extraction of granular material is the major tool in preventing the buildup of the channel bed to unacceptable levels. On the other hand, in other areas of the same country, excessive mining of sand and gravel from the river bed has led to severe channel degradation, and the undermining of river bed and bank structures.

One obvious issue on the Mackenzie is the degree to which any mining of material in the lower reaches near Point Separation would initiate bed scour of Delta channels, such as the East Channel, where pipelines may be buried beneath the bed surface. The environmental repercussions of depleted sand influxes to the Delta, given the issues noted in Section 2, also need addressing, though the amount of mining that might take place in the lower Mackenzie could be limited by the fineness of the bed sediment there: limited particle size data for bed material in the Mackenzie upstream of Arctic Red River (at 10LA003) indicate silt fractions ranging up to 24 percent.

Further upriver on the Mackenzie, impacts could be both negative and positive. Undermining of pipes in the Norman Wells area by bed scour looms as a worry. Yet, in navigation problem areas, mining of the bed material might prove advantageous. The report by Acres (1987), for example, dealt with several different dredging scenarios. At one extreme was the option recommended by the Northern Transportation Company Limited (122 m wide channel, 2.44 m deep) that involved almost 2 million cubic metres of initial dredging. At the other extreme was the minor programme recommended by Acres in terms of benefit:costs ratios, an option that involved dredging only at the four sites where relaying is currently required. This would require an initial dredging quantity of only 200,000 cubic metres. The terms of reference of the Acres report do not appear to have included demand for the spoil of the dredging operations noted above in connection with on-land construction. If this were included, the benefit:cost ratios (applied to both dredging and utilization of granular material) for the different scenarios might be quite different, possibly justifying a larger dredging programme. To a large extent, this would, of course, depend on the quality of the dredged material: not all of it is alluvial, and not all of it is suitable for construction material.

An environmental issue of some significance, arising out of mining of the river bed, is the impact on fish. Riverbed areas of granular sediment are usually favoured sites of spawning; hence mining could have serious effects on fish stock. Whether

or not this is likely to occur, however, will depend to a large extent on the degree of utilization of the main stem (as distinct from tributaries) for spawning by different species. Little appears to be known about this matter. It is certainly beyond the terms of reference of this study, and, for this reason, the general issue of impacts of riverbed mining on fish will not be pursued in any detail below.

(b) INFORMATION NEEDS

To assess the impact of mining sand and gravel from the Mackenzie bed on the river system requires information initially as follows. How much suitable borrow material exists on land in the corridor, and where is it located? How much suitable borrow material is available in the Mackenzie river bed, and where is it located? What are the comparative costs of extracting and transporting granular material on land and in the channel? Answers to these questions will indicate the likely sources of granular material to be used along the corridor.

The next suite of questions involves the amount and rate of extraction of such river bed material relative to actual transport rates within the river. The need for the latter data has already been emphasized in Sections 6 and 7, and emphasizes again how interdependent these various issues are in their information requirements.

(c) ADEQUACY OF EXISTING INFORMATION

Preliminary answers to the first suite of questions have been provided by EBA (1987). Their report indicates that about two-thirds of the Mackenzie Valley lack suitable granular material for construction purposes within 15 km of the riverbank. This is particularly true of the first 500 km from Great Slave Lake to about McGern Island. It was also noted to apply to km 750-875 (Keele River almost as far as Norman Wells), km 1000-1100 (Axel Island to Fort Good Hope) and km 1325-1475 (upriver of Barrel Crossing to Point Separation). In most of these areas the valley material is glaciolacustrine silty-clay sediment.

The same report indicates a high potential for granular borrow material from 22% of the Mackenzie river bed. This conclusion was based on a rating system in which channel braiding, steep river gradients and proximity of gravel-bed tributaries were seen as indicators of suitable granular alluvium. It is worth emphasising that the notion of utilizing Mackenzie riverbed sediment as a source of borrow material was bolstered by the success of Esso Resources Canada Ltd in dredging bed sediment at Norman Wells for the construction of artificial islands. EBA (1987) notes that, while preliminary sampling had suggested that the river bed there was silty sand, most of the dredged fill, in fact, turned out to be sandy gravel.

Based on the report by EBA (1987), mining of sand and gravel from the Mackenzie river bed therefore looms as a major disturbance of the Mackenzie sediment system. As might be expected, most of the river reaches with high potential coincide with areas in which abundant granular material is available on the valley flanks (usually the right bank). Close inspection of the EBA (1987) report (drawing 4-1), in fact, indicates only two reaches in which the river bed potential is high or moderately-high and the adjacent valley flank is deficient in granular material. These are km 450-475 (Camsell Bend) and km 1017-1030 (Sans Sault Rapids).

In view of the observations above, it might seem that the potential for borrow material in the Mackenzie river bed, relative to that on the north bank, is limited. The key issue here, however, is cost, and, in particular, the cost of transporting the borrow material. Though accurate pricing is difficult, EBA (1987) estimated the cost of barge transport of river material to be less than half of that for road haulage on land. The analysis indicated that costs of river operations would be more economical than land exploitation where hauls of greater than 7 km were involved, the disparity increasing with distance of haul. Given that this seems to apply to at least two-thirds of the Mackenzie Corridor, the demand for granular river bed material is likely to be significant.

EBA (1987) also reviewed the environmental implications of such extraction. They concluded that resuspension of fines during extraction would provided minimal changes in the suspended load of the Mackenzie, based on assessment of monitoring data associated with dredging by Public Works Canada. They also noted that participants in the Mackenzie Environmental Monitoring Project (MEMP, 1986) felt that the effects of mining on the channel morphometry and bed material composition would be relatively short-lived (given the assumed existing high rates of bedload transport) unless the volume of excavated material is large in relation to these loads. As noted above (a), there is some justification for the latter concern.

In terms of the impact on the stream bed, it should be recalled (Section 10) that the Norman Wells Expansion Project involved dredging of almost 2 million cubic metres of granular material from the Mackenzie, primarily for island construction but also for pipeline trench fill and roads. A series of annual bathymetric surveys of the project area was undertaken for Esso in 1983 (by Canadian Engineers Surveys Co. Ltd) and 1984-1986 by W.D. Usher and Associates Ltd, and could, if extending sufficiently far upstream and downstream, provide invaluable information regarding the response of the river to the mining of bed material. These charts should be examined and the changes used as a guide in planning future monitoring programmes at sites of mining of bed material.

(d) RECOMMENDATIONS

As EBA (1987) points out, the scarcity of bed material data for the Mackenzie makes it impossible to provide an accurate determination of just how much suitable borrow material is available. They have recommended to INAC that a riverbed inventory should be undertaken, focussing on reaches with moderate to high ratings of potential which are close to areas where shortages of upland borrow exist. Essentially, this corresponds to km 50-100 (Providence Rapids), km 275-500 (Jean Marie River to McGern Island), km 700-900 (Redstone River to Norman Wells), and three very short reaches in the lower river, km 1000-1050 (Axel Island to Hume River), km 1150-1175 and km 1275-1300. It should be noted that these stretches of river include many of the areas designated as priority dredging for navigation purposes (Fig. 13). Acres (1987) recommended that surveys of bed material be undertaken in these priority dredging areas. Overall, our meagre knowledge of the bed sediments of the Mackenzie represents a marked contrast to information gathered by the Geological Survey of Canada for the surficial deposits of the flanking terrain.

11.1. Given the scarcity of reliable bed material data for the Mackenzie River, and given the demand for such data, the Water Resources Branch should assume the initiative in establishing a programme for verifying the nature of the bed sediment at strategic locations along the river.

This work should be done in liaison with both INAC (responsible for borrow material extraction) and the Coast Guard (responsible for navigation). Users of this information might be expected to contribute to the investigation. Surficial sampling alone will be inadequate. Geophysical methods will need to be employed to assess thickness of the alluvium, and subsurface sampling will be needed to verify the type of material at depth. Split-spoon sampling is not likely to be suitable for this purpose, as noted by EBA (1987), because of poor recovery in granular soils. The work would provide data indispensable to many issues of practical significance on the Mackenzie, as well as baseline data so important in developing a budget for bed material movement along the main stem.

In terms of the environmental implications of dredging and extraction, the most serious appear to be those involving (i) downstream scour or (ii) impacts on fish, especially in spawning areas. The severity of these impacts simply cannot be assessed without (i) much more information on bed material transport rates along the length of the Mackenzie, and (ii) much more knowledge of the use of the mainstem Mackenzie by the major fish species.

Recommendations for acquiring more information on bed material transport loads along the Mackenzie have already been put forward, in some detail, in Chapter 6. The issues addressed here, like those in the four previous sections, emphasize just how important this "scientific" information is in management of the Mackenzie River.

In terms of impact on fish, EBA (1987) emphasized that while information regarding fish utilization of tributaries has become available in the last twenty years, a great deal of ignorance remains regarding the main stem. The environmental lobby cannot be taken seriously until it provides much more data on the utilization of the Mackenzie by the major fish species. Recommendations in this context, however, fall beyond the domain of the present report.

PART THREE

SUMMARY OF RECOMMENDATIONS

In most cases, the importance attached to each recommendation has been indicated above. Nonetheless, in examining the recommendations as a whole, it is worth emphasizing two points:

1. analysis of existing data should be undertaken before new data are collected;

2. in many cases, timing is critical in the implementation of these recommendations, as is the coordination among different subprojects.

The various recommendations put forward in Part Two of the report are summarized below. They have been grouped in distinct suites, recognizing that there is much in common between individual suggestions, and that implementation of one is best done as part of the entire set.

A. Review of suspended sediment data

The most urgent need is for full sediment station reviews for stations 10LA002, 10LA003, 10MC002, 10ED002 and 10GC004 as outlined in Recommendations 2.1, 2.2, 2.3, 5.1 and 5.4. These are necessary to assess the accuracy of existing data, reconcile apparent inconsistencies, and identify in more detail areas where the sampling programme must be strengthened. Ultimately, it will allow assessment of whether, and when, routine sampling at these stations can be abandoned, allowing redeployment of resources elsewhere.

B. Analysis of existing bathymetric charts

Equally urgent is an analysis of bed material yields in different reaches along the Mackenzie, using available bathymetric sheets from the Canadian Hydrographic Service, as outlined in Recommendations 6.2.1a, 6.4.1 and 6.5.2. This will provide a clearer indication of the potential of this method, prior to embarking upon further survey work.

C. Additional bathymetric surveys

Assuming that the results of the previous set of analyses (B) are acceptable, further bathymetric survey work should be undertaken as outlined in Recommendations 6.1, 6.2.1b, 6.2.3, 6.4.2, 6.4.3, 6.5.1, 6.6. There is some additional urgency for this work in connection with current proposals for dredging (Section 7(d)) and mining of the Mackenzie bed (Section 11 (d)), both emphasizing the practical importance of the recommendations in Section 6. Related to this topic is further investigation of the actual composition and thickness of the bed alluvium in key areas of the main stem (Recommmendation 11.1).

D. Establishment of new suspended sampling stations

Also urgent is the establishment of new suspended sediment sampling stations near the mouths of the three main Delta distributaries (Recommendation 1) and at Wrigley, Norman Wells and Fort Good Hope (Recommendations 5.3, 6.5.3, 7).

E. Expansion of existing and new sediment stations to include nutrients, hydrocarbons and metals

After an initial year's sampling at the new sites listed above (D), in which cross-sectional variance in concentration and particle size has been established (together with patterns in the temporal fluctuation), sampling at these new sites, along with relevant established sites, should be expanded to include nutrients (Recommendations 3.1, 3.2), hydrocarbons (Recommendations 4.1.1 and 4.1.2) and heavy metals (Recommendation 4.2).

Thus, in terms of suspended sediment, Suite A should be undertaken first; Suite D is a second stage; and Suite E a third stage. On the other hand, it would seem sensible now to establish interest and support among potential users of the information on suspended sediment (identified at various places in the text), so that the framework for the second and third stages is ready by 1989.

In terms of bed material loads, Suite B represents a first stage prior to implementation of the new surveys of Suite C. The urgency to implement this aspect of the work is almost as great as that dealing with suspended sediment. On the other hand, it seems likely that planning future surveys will take some time, and is unlikely to be completed in time for new surveying by the start of the 1989 fiscal year. A more realistic goal is the start of 1990. Thus Suite B could be deferred until 1989, followed by new surveys in 1990-1991.

The immediate task in connection with Suite C is identification of the most appropriate agencies to undertake the work. There are two types of survey involved : sampling of bed material (Rec. #11.1) and bathymetric surveys (Rec. #6.1 et seq.). The former will require discussion among Water Resources Branch, Indian and Northern Affairs, the Coast Guard, and possibly other parties (See Section 11). In terms of the latter, some of the routine surveys are probably best continued by the Canadian Hydrographic Service; the more specialized (e.g. annual surveys of a specific reach e.g. Rec. #6.2.3) may be more suited to the bathymetric survey section of the Water Resources Branch. On the other hand, a key element in cost will be overheads in the field, and these would be reduced by one party assuming full responsibility.

F. Increased research into ice-jamming and channel scour under ice conditions

Basic research into ice-jamming in relation to channel shoaling and into the effects of an ice cover on short term bed scour should be increased (Recommendations 8.1, 9.1, 10.2). Though there is no immediate urgency, the issues are of some importance in the long term.

G. Minor issues

The remaining recommendations dealing directly with sediment issues are 5.2 (determination of sediment contributions from bank erosion along the main stem) and 6.2.2 (estimation of the bed material load of the Peel near its mouth). The photogrammetric component of these two studies is not likely to be costly and therefore could be done soon. Field verification may be much more expensive, and should be deferred until the photogrammetric results have been appraised.

H. Utilization of the main stem by fish

The need for a more thorough understanding of the utilization of the Mackenzie main stem by major fish species (Section 11 (d)) is of vital importance in any assessment of the impact of land use change on the native peoples of the region. It is listed at the end of this summary, only because it is not obvious that the major impacts on fish resources are sediment-related. This does not mean that the work is neither important nor urgent; it is.

Conclusion

One point that clearly emerges from reviewing the literature dealing with the Mackenzie, including reports from ongoing research, is that much of the data being collected could be more useful than it currently is. The problem is that numerous projects are being undertaken, by different government departments, without, it would seem, any clear coordination of policy. Indeed, in many cases, one department does not know what another is doing even though their work is directly related.

A clear, overall, monitoring programme in terms of sediment and water quality must be set up for the entire basin, at least downstream of Great Slave Lake and offshore to the Beaufort Sea. This should go some way to ensuring that data collected upstream can be related to data being collected in the Delta and offshore. In the same way, methods of analysis have to be standardized. If, for example, hydrocarbon fluxes from the river are to be related to hydrocarbon concentrations in the Beaufort Sea, then this requires that the same hydrocarbon compounds be measured upstream and offshore, and by the same sampling, storage and analytical procedures. Similarly, it is clear that parts of the Mackenzie river bed will need to be dredged to increase naviga-

tion capacity, while some parts may be desirable as sources of granular material for on-land construction. It is not obvious that these two topics have previously been seen as two sides of the same coin.

In general, what is indicated by this analysis is that some agency, even if only one person, should be responsible for coordinating research and development within the Mackenzie basin. Without this there will be both unnecessary duplication of effort and failure to perceive that the action of one organization has implications for others. Such a philosophy is not entirely without precedent. The holistic view with regard to river basin management is the raison d'etre, for example, of the River Authorities in the United Kingdom and the Catchment Authorities in New Zealand. While it may be unnecessary to adopt this kind of approach for each major basin in Canada, certain key catchments, such as the Mackenzie, would seem to be ideal candidates for action along these lines.

In fact the Mackenzie Basin Intergovernmental Liaison Committee was formed in 1972 largely for this purpose: to exchange information concerning project planning, research and potential developments. It was reestablished in 1977 as the Mackenzie River Basin Committee, the immediate purpose of which was implementation of a three-year study agreement (1978-81) comprising research into various aspects of the water-related resources and hydrological behaviour of the Mackenzie basin, including its tributaries upstream of Great Slave Lake. Since that time the Committee has been effecitve in reporting research done in the basin (e.g. in its annual reports), but its role in the planning and coordination of work is less apparent.

Overall recommendation. An organization be established, or an individual appointed, whose full-time responsibility is the coordination of sediment and water-related issues in the Mackenzie basin.

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APPENDIX

TABLES 1 TO 11

	Mackenzie 10LA003	Arctic Red 10LA002	Peel 10MC002	Total
Jan.	0.1	0.0	0.0	0.1
Feb.	0.1	0.0	0.0	0.1
March	0.1	0.0	0.0	0.1
April	0.1	0.0	0.0	0.1
May	17.8	2.0	13.6	33.4
June	33.9	2.2	12.6	48.7
July	18.7	0.8	1.8	21.3
Aug.	10.3	2.0	1.9	14.2
Sept.	4.1	0.1	0.5	4.6
Oct.	2.3	0.0	0.1	2.4
Nov.	0.6	0.0	0.0	0.6
Dec.	0.1	0.0	0.0	0.1
Total	88.2	7.1	30.5	125.8

TABLE 1

INPUTS OF SUSPENDED SEDIMENT TO THE MACKENZIE DELTA:
MONTHLY AND ANNUAL MEAN TOTALS IN MEGATONNES, 1974-1983

(after Lewis, in prep.)

	May	June	July	Aug.	Sept.	Oct.	Total
1972			1	1	1		3
3		6	8	6	3		23
4		1	6	3	3		13
5		2	2	1	2	1	8
6							0
7							0
8							0
9							0
1980		9	9	7	8		33
1	1	10	6	6	12	8	43
2		12	14	14	4	2	46
3		21	9	5		2	37
Total	1	61	55	43	33	13	206
1984	2	29	24	6	3	3	67
1985		14	19	10	5	5	53
Total	3	104	98	59	41	21	326
Mean load (Mt)	17.8	33.9	18.7	10.3	4.1	2.3	

TABLE 2

NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT ON MACKENZIE RIVER UPSTREAM OF ARCTIC RED RIVER (10LA003)

(Mean load refers to period 1974-1983: Table 1)

	May	June	July	Aug.	Sept.	Oct.	Total
1972		1	2	2	2		7
3		7	8	7	3		25
4			6	4	4		14
5		3	3		3	1	10
Total		11	19	13	12	1	56
Mean load (Mt)	2.0	2.2	0.8	2.0	0.1	0.0	

TABLE 3

NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT ON ARCTIC RED RIVER (10LA002)

(Mean load refers to period 1974-1983: Table 1)

	May	June	July	Aug.	Sept.	Oct.	Total
1972			1		1		2
3			13	5			18
4		2	3	4	2		11
5		12	11		1		24
6		1	9	8	4		22
Total		15	37	17	8		77
Mean load (Mt)	13.6	12.6	1.8	1.9	0.5	0.1	

TABLE 4

NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT ON PEEL RIVER UPSTREAM OF FORT MCPHERSON (10MC002)

(Mean load refers to period 1974-1983: Table 1)

	Fort Providence	Wrigley	Norman Wells	Mackenzie 10LA003
	1968-80	1972-75	1960-78	1960-80
Dissolved nitrogen	18	0	0	12
Total Kjeldahl nitrogen	38	23	7	34
Dissolved nitrates (-ites)	58	26	82	68
Total dissolved phosphorus	22	3	3	14
Total phosphorus	0	22	34	0
Total organic carbon	37	24	13	49

TABLE 5

NUMBER OF NUTRIENT DETERMINATIONS MADE ALONG MACKENZIE RIVER 1960-1980

(based on Table E-1g, MRBC, 1985)

Site	km	1985 Turbidity NTU	1985 Alkanes in sed ng/gm	1986 Turbidity NTU	1986 Total sediment in water mg/l	1986 Alkanes in sed ng/gm	1986 PAH's in sed ng/gm
Liard		42	588	62	87	99	264
Martin Is	329	8	3676	11	11	1523	418
Wrigley	577	22	824	53	83	791	196
Halfway I	848	18	412	288	519	125	52
N. Wells	901	56	1743				
N. Wells	902	50	1972				
Hardie Is	1044	55	1158	336	685	205	76
	1142			288	492	255	147
Arctic Red	1444	84	1272	156	364	1116	391
Inuvik	1687			172	349	773	289

TABLE 6

SEDIMENT AND HYDROCARBON DATA, MACKENZIE RIVER, 1985 AND 1986

(compiled from Nagy et al., 1986 and 1987)

The Liard value for n-alkanes in 1986 is based on Nagy et. al (1987) Fig. 3 and not on their Table 3, which appears to contain an error in the position of the decimal place.

Site	km	Alkanes as sed in water ng/l	Alkanes free in water ng/l	Alkanes total in water ng/l	PAH's as sed in water ng/l	PAH's free in water ng/l	PAH's total in water ng/l
Liard		86	284	370	23	292	315
Martin Is	329	17	591	608	5	1824	1829
Wrigley	577	66	147	213	16	303	319
Halfway I	848	65	239	304	27	111	138
N. Wells	901						
N. Wells	902						
Hardie Is	1044	140	410	550	52	414	466
	1142	125	505	630	72	1234	1306
Arctic Red	1444	406	168	574	142	261	403
Inuvik	1687	269	219	488	101	54	155

TABLE 7

HYDROCARBON CONCENTRATIONS IN MACKENZIE RIVER, AUGUST 1986

(based on Nagy et al., 1987)

	May	June	July	Aug.	Sept.	Oct.	Total
1972		1	3	1	1		6
73	10	18	15	13	6	3	67
74	6	15	9	8	4		42
75			1	3	5		9
76	2	13	7	6	4	1	33
77							0
78							0
79		18	10	9	4	2	43
80	5	7	5	5	5	3	30
81	3	5	4	1	1	1	15
82	2	6	5	3	3	1	20
83	6	7	8	4	3	1	29
84	8	8	6	5	4	1	36
85	5	5	5	2	2	2	21
Total	47	103	78	60	42	15	351

Annual totals include 2 April days in 1973 and 4 April days in 1984

TABLE 8

NUMBER OF DAYS SAMPLED FOR SUSPENDED SEDIMENT ON LIARD RIVER NEAR THE MOUTH (10ED002)

	May	June	July	Aug.	Sept.	Oct.	Total
1973	4.7	33.4	6.8	0.9	0.9	0.2	46.9
1974	7.1	11.7	17.5	6.7	0.8	0.5	44.3
1975	1.6	15.9	20.5	4.2	0.5	0.2	42.8
1976	3.9	17.9	28.5	9.4	2.0	0.3	62.0
1977	5.8	54.5	11.6	3.3	0.6	0.2	75.9
1978	1.1	4.6	1.7	0.9	0.8	0.2	9.3
1979	4.2	21.3	22.5	2.0	0.9	0.2	51.2
Mean	4.1	22.8	15.6	3.9	0.9	0.2	47.5

TABLE 9

MONTHLY SUSPENDED LOADS OF LIARD RIVER NEAR ITS MOUTH (10ED002) 1973-1979 IN MEGATONNES

(after BC Hydro, 1984, Table 4-3(b))

River	Maximum Elevation m	Basin Area sq. km.	Stream Slope m/100 km	Stream Power Index	Suspended Sediment Load Mt
Peel	1676	78746	116	15252	11.1
Keele	1753	27110	265	12598	9.2
Redstone	2134	15747	366	12282	8.9
Arctic Red	2286	21456	199	9754	7.1
Root	2286	9933	413	9375	6.8
Mountain	1524	14983	398	9082	6.6
North Nahanni	2286	7125	436	7095	5.2
Johnson	1219	2214	826	2229	1.6
Dahadinni	1067	2709	485	1401	1.0
Wrigley	762	1300	820	813	0.6
Carcajou	1981	9135	36	651	0.5
Willowlake	335	21184	51	363	0.3
Two Mountains	396	3484	223	308	0.2
Hare Indian	259	11352	63	184	0.1
Travaillant	290	2911	112	94	0.1
Tieda	351	945	269	89	0.1
Ontaratue	152	6853	59	61	0.0
Gull	99	1715	74	13	0.0

The stream power index is the product of elevation, area and slope divided by 1,000,000. Small apparent errors are due to rounding.
The estimate of suspended sediment load is derived by scaling down (or up) the actual load of the Arctic Red River by an amount equal to the ratio of the power index of the tributary in question to the power index of Arctic Red.

TABLE 10

MORPHOLOGIC DATA FOR MAIN TRIBUTARIES
AND ESTIMATES OF ANNUAL SUSPENDED LOAD

(data for elevation, area and slope from
Thakur and Lindeijer, 1973)

	km	chart	dates		
Point Separation	1480				
Arctic Red River		6426	1973	1977.78	New
	1400				
Barrel Crossing		6425	1973	1978	New
	1325				
		6424	1972	1979	
	1240				
		6423	1973	1979	
	1180				
		6422	1972	1979	
Fort Good Hope	1100				
Hume River		6421	1971		New
	1040				
Mountain River		6420	1971		New
	980				
		6419	1971	1978	New
Norman Wells	910				
		6418	1973		
	850				
		6417	1973		
	810				
Keele River		6416			New(P)
	730				
Redstone River		6415			New(P)
	650				
		6414			
	580				
Wrigley		6413	1972		
	510				
		6412	1972	1978(P)	
N. Nahanni River	460				
		6411		1979	New
	390				
		6410			
Liard River	330				

N.B. (P) denotes part of sheet

TABLE 11

FULL CHART SURVEYS OF MACKENZIE RIVER
BY CANADIAN HYDROGRAPHIC SERVICE

Existing and recommended

APPENDIX

FIGURES 1 TO 13

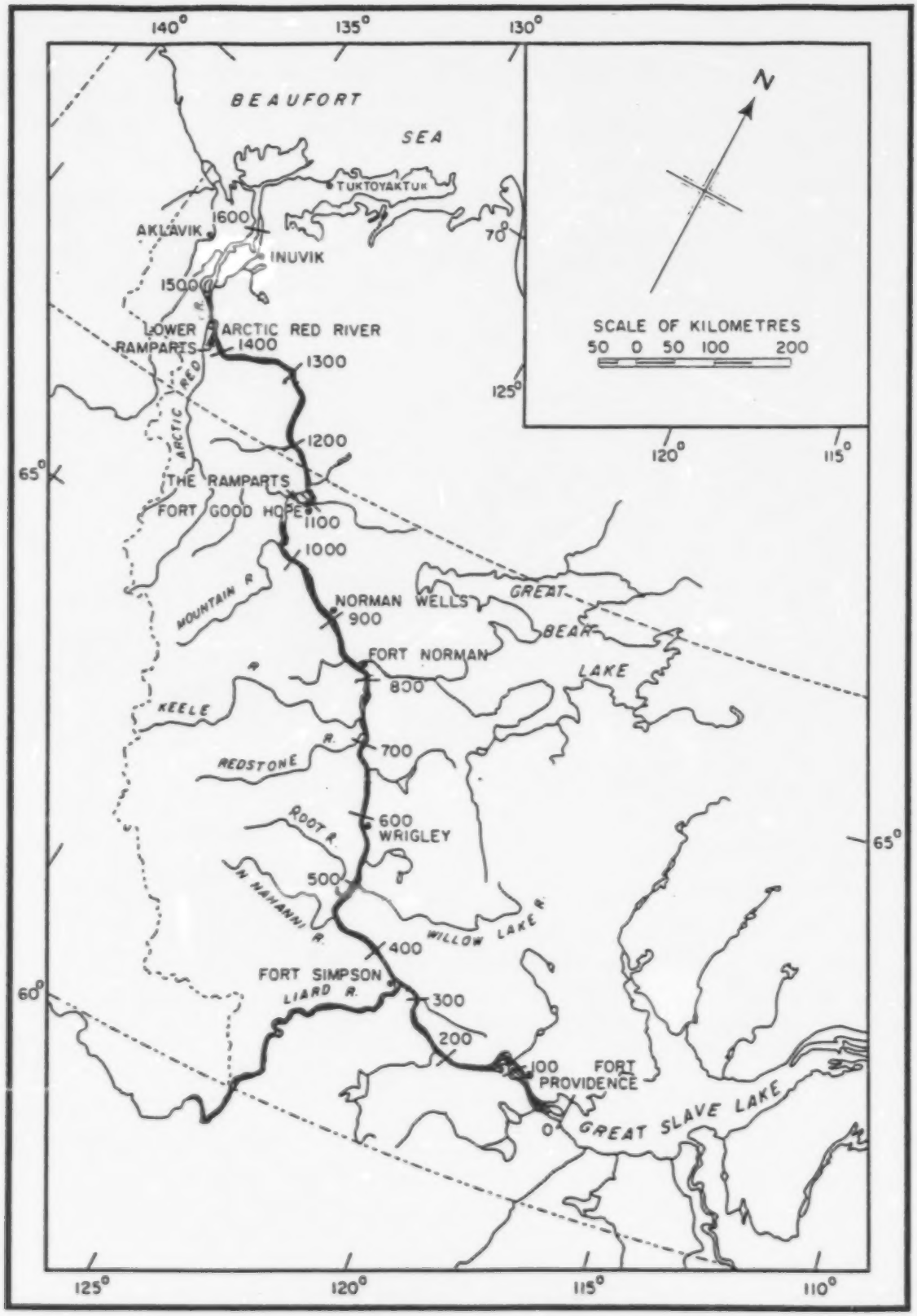


FIGURE 1 LOWER MACKENZIE BASIN : LOCATION MAP

(modified after MacKay, 1973)

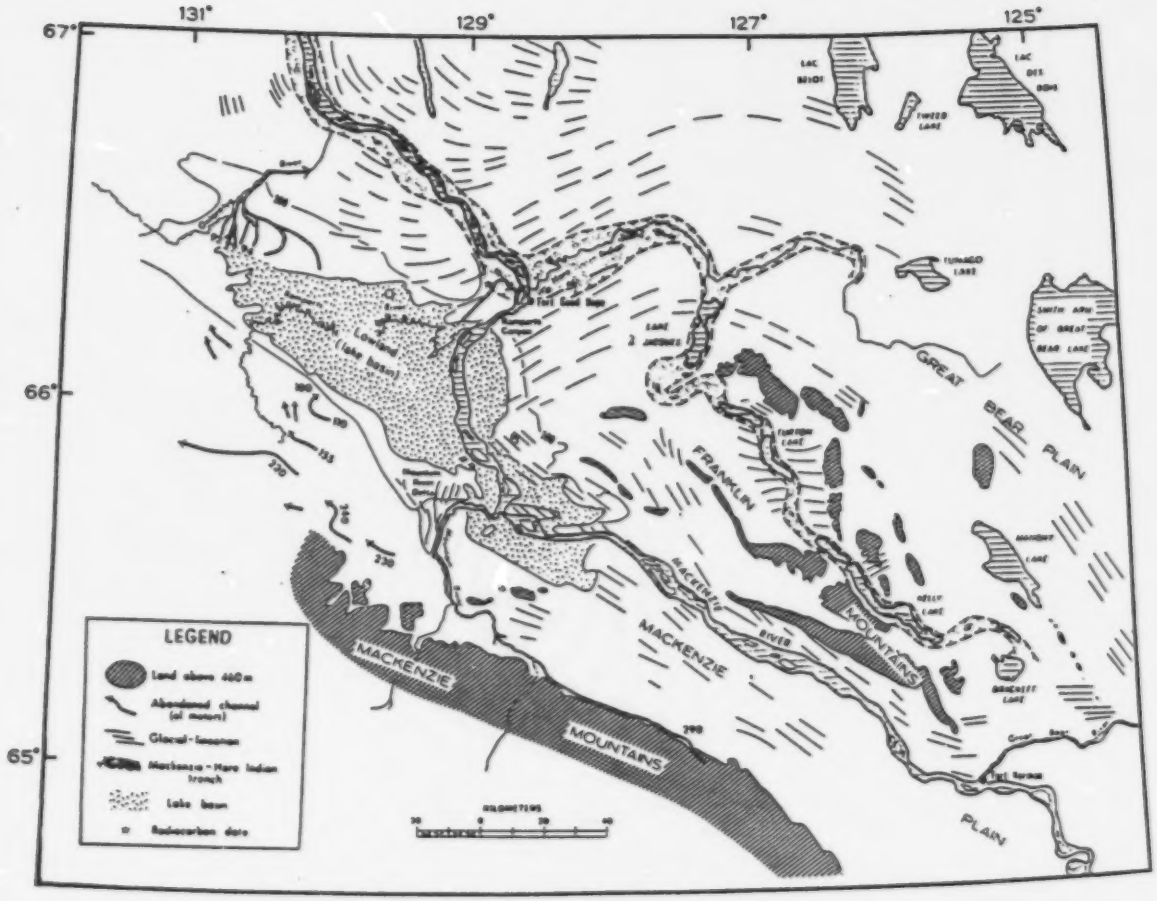


FIGURE 2 TERRAIN FEATURES OF THE FORT GOOD HOPE REGION

(modified after Mackay and Mathews, 1973)

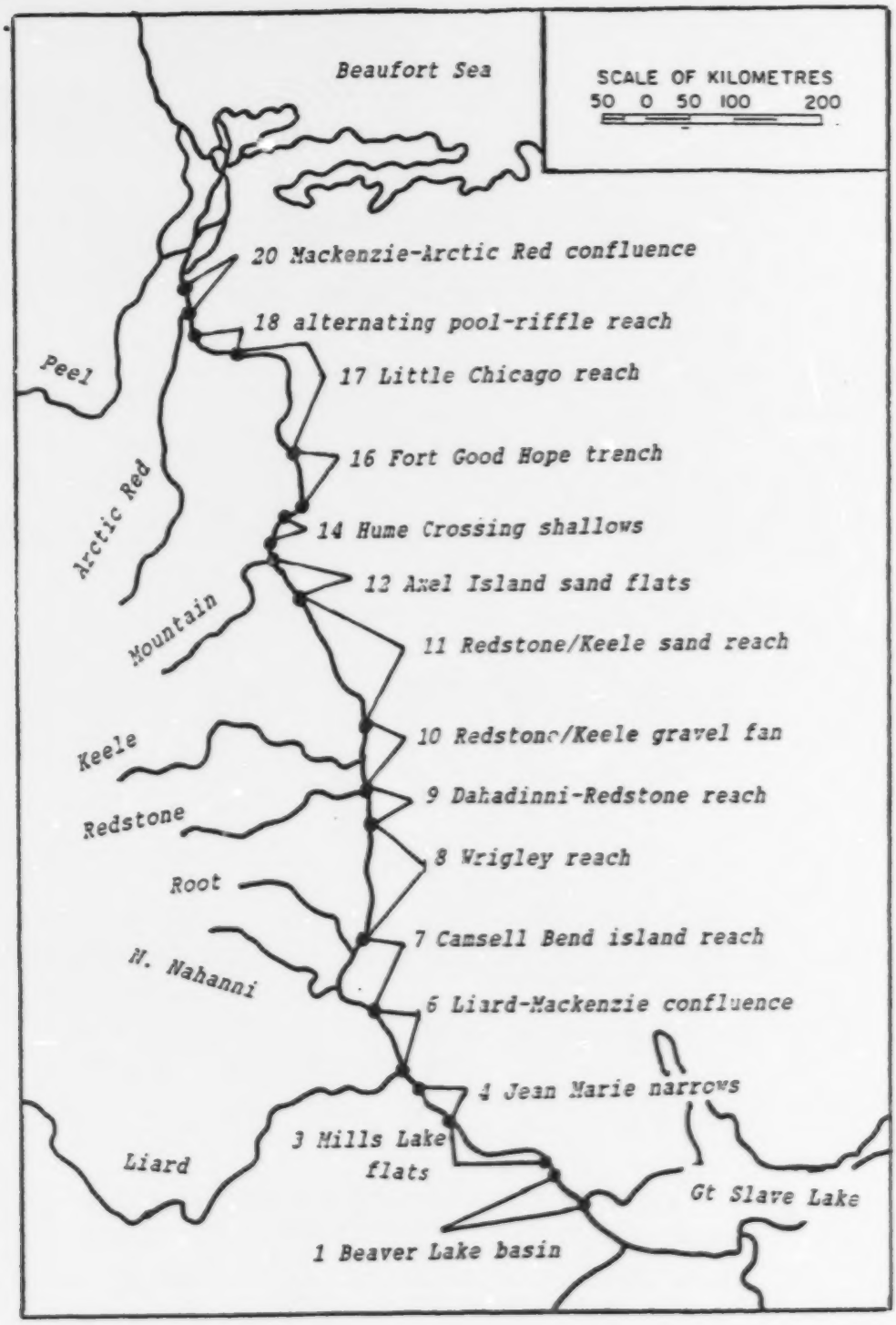


FIGURE 3 REACHES OF THE MACKENZIE RIVER

unnumbered reaches are rapids: 2: Providence 5: Green Island 13: Sans Sault 15: Ramparts; 19 is Lower Ramparts bend

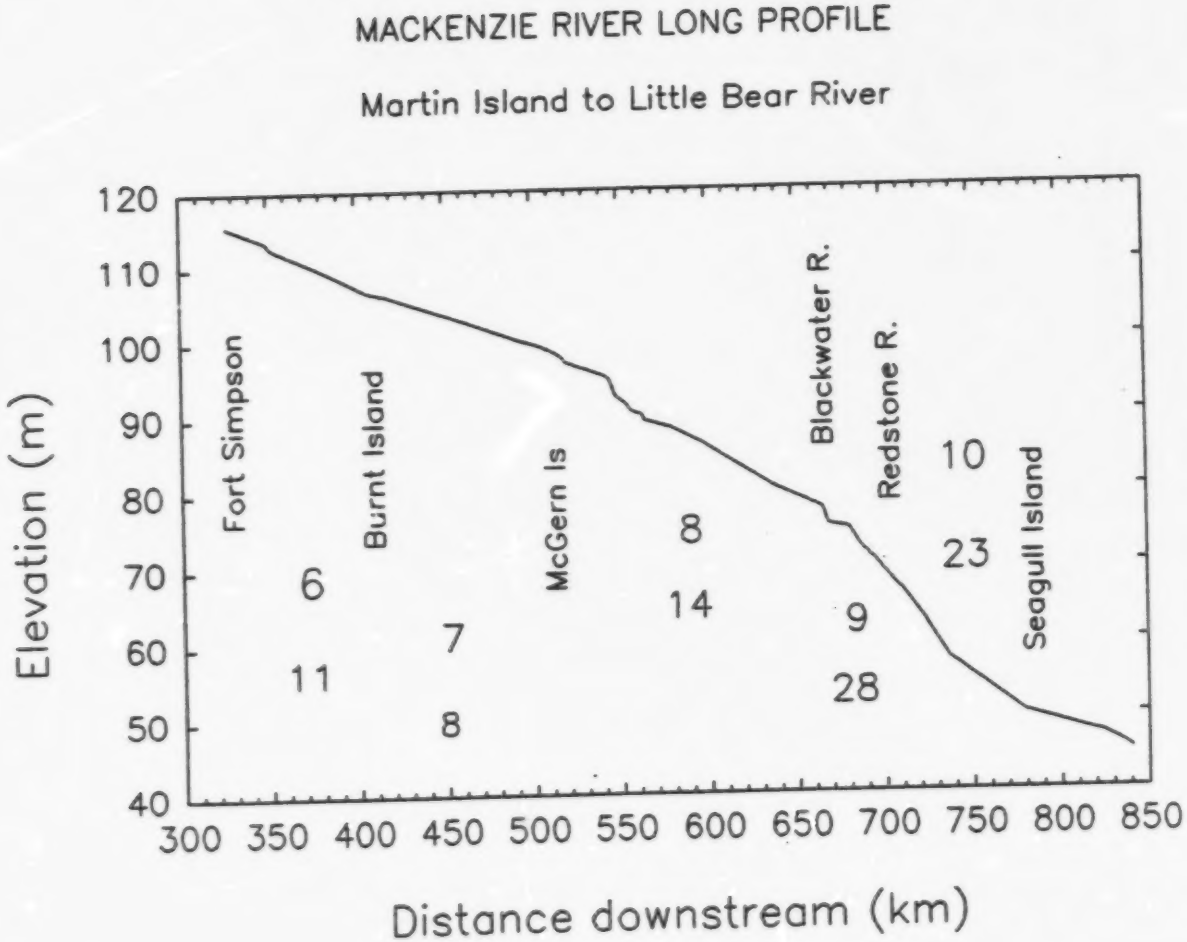


FIGURE 4a MACKENZIE RIVER LONG PROFILE:
Martin Island to Little Bear River

(based on data from Geodetic Survey of Canada in Public Works Canada, 1976)

Values are reach number (top) and gradient in m/100 km

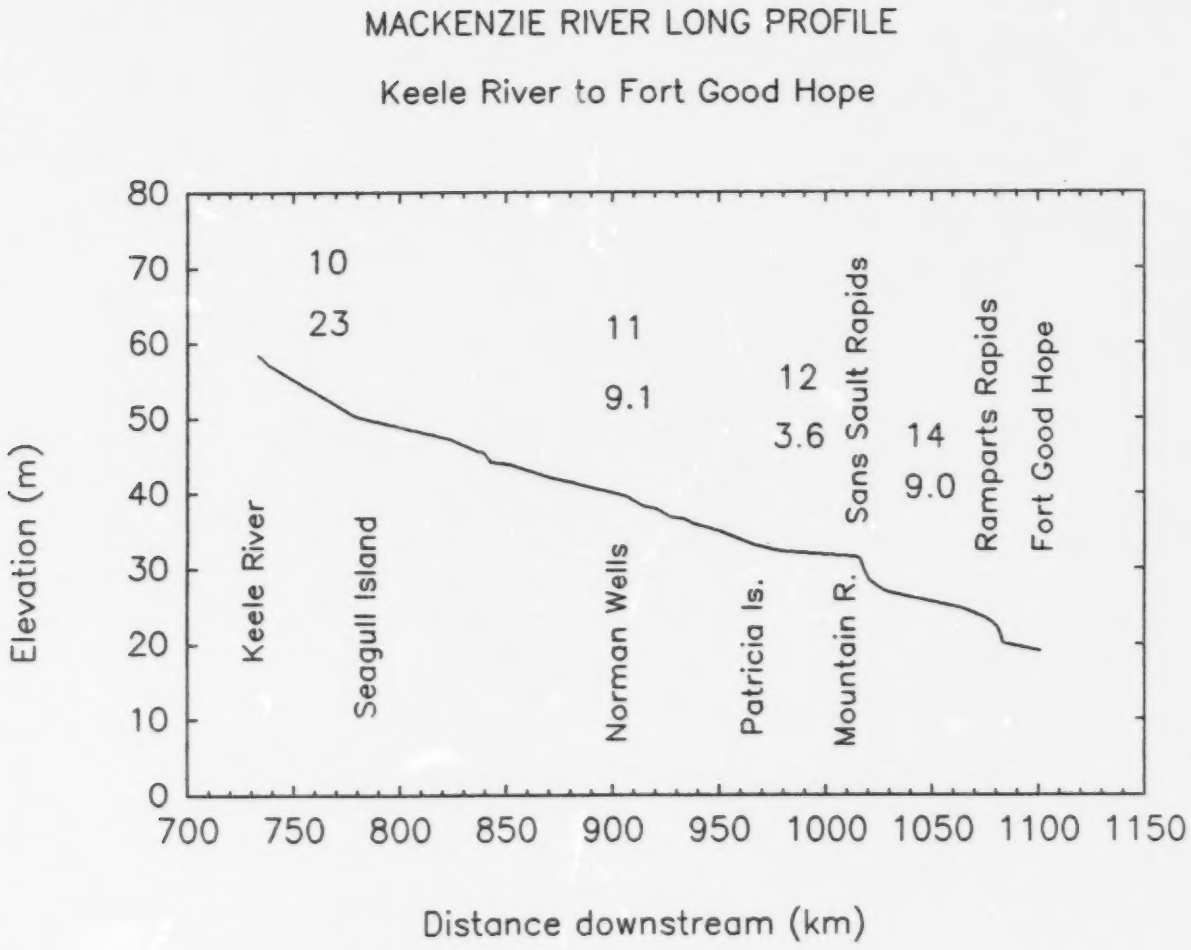


FIGURE 4b MACKENZIE RIVER LONG PROFILE:
Keele River to Fort Good Hope

(based on data from Geodetic Survey of Canada in Public Works Canada, 1976)

Values are reach number (top) and gradient in m/100 km

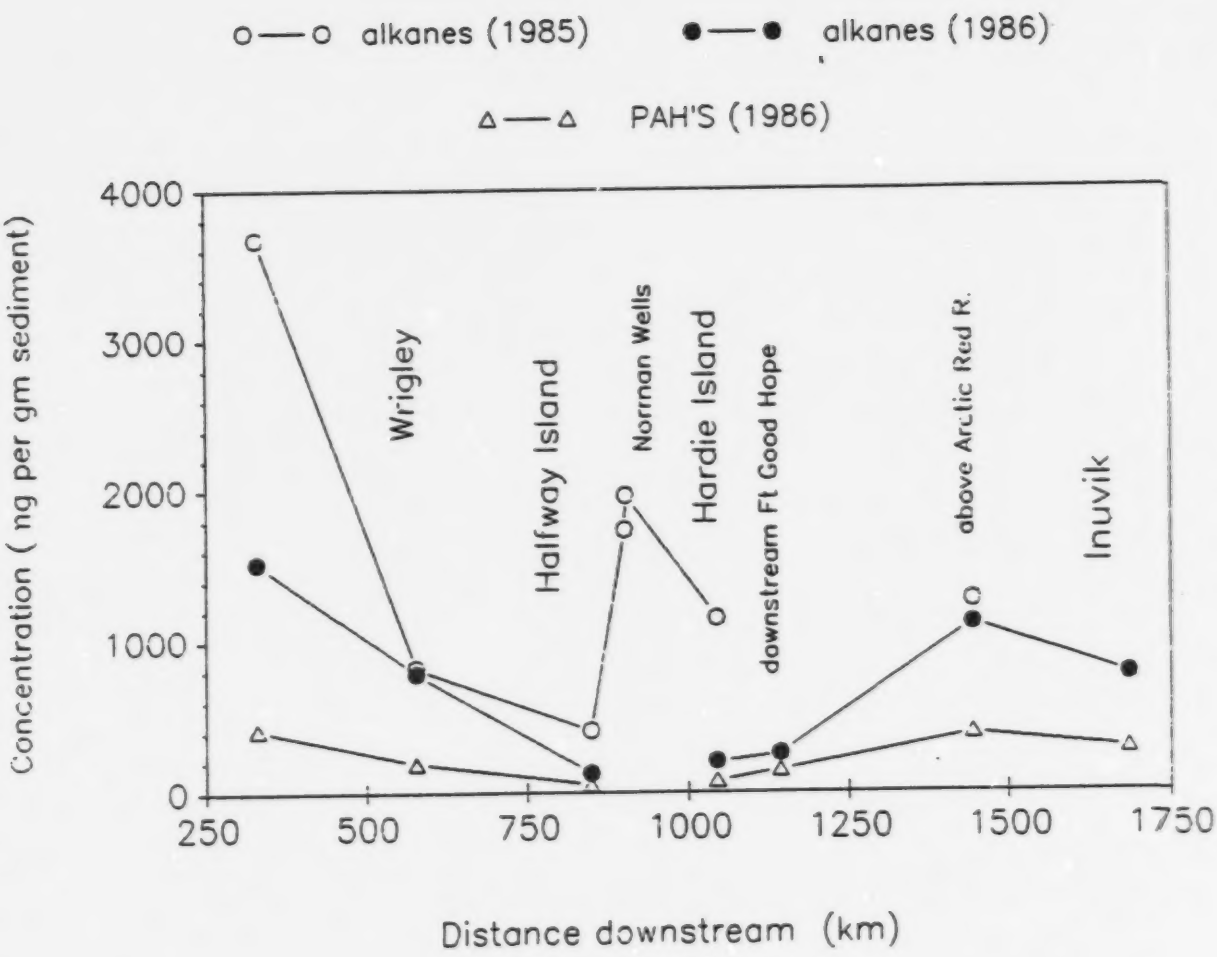


FIGURE 5 DOWNSTREAM CHANGES IN HYDROCARBON CONTENT OF SUSPENDED SEDIMENT: Mackenzie River, 1985 and 1986

(based on data from Nagy et al., 1986, 1987)

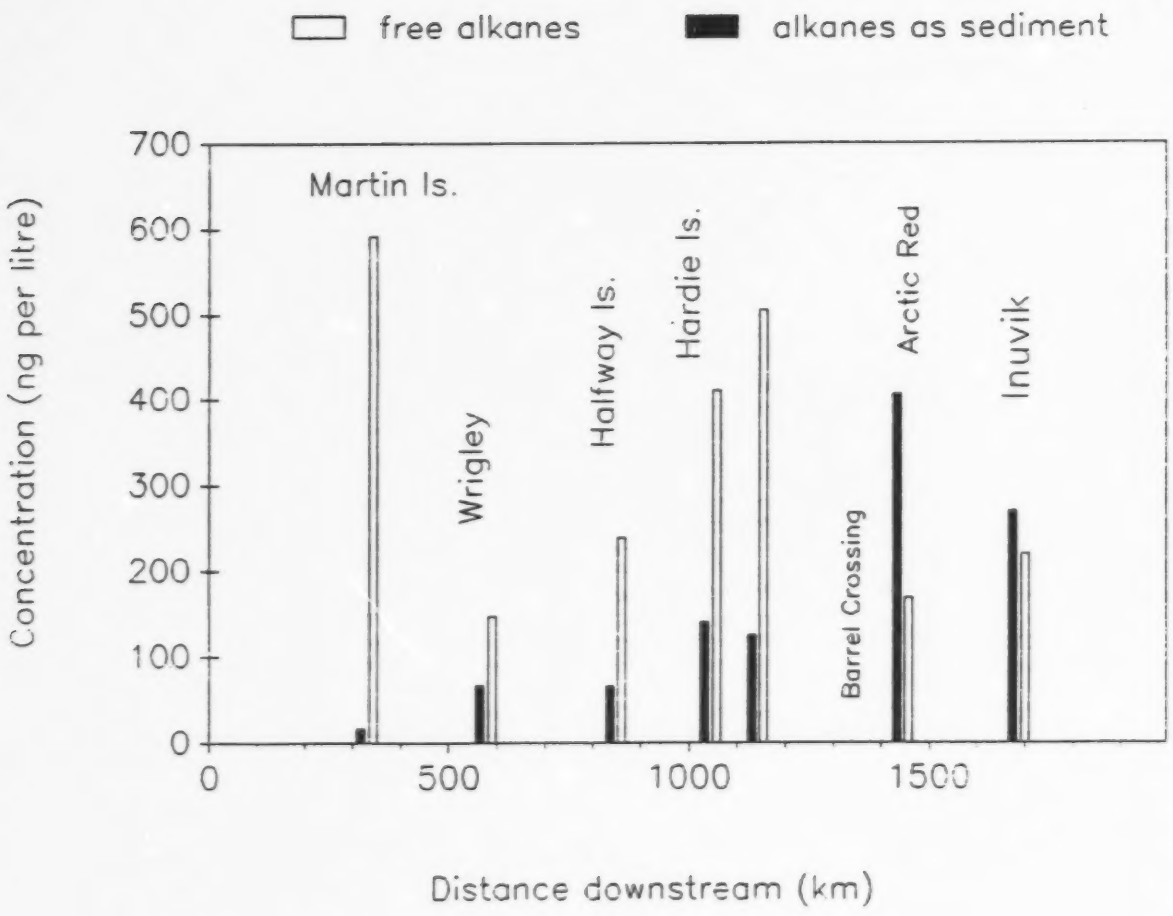


FIGURE 6 CONCENTRATION OF ALKANES IN WATER AND SUSPENDED SEDIMENT: June 1986
(based on data from Nagy et al., 1987)

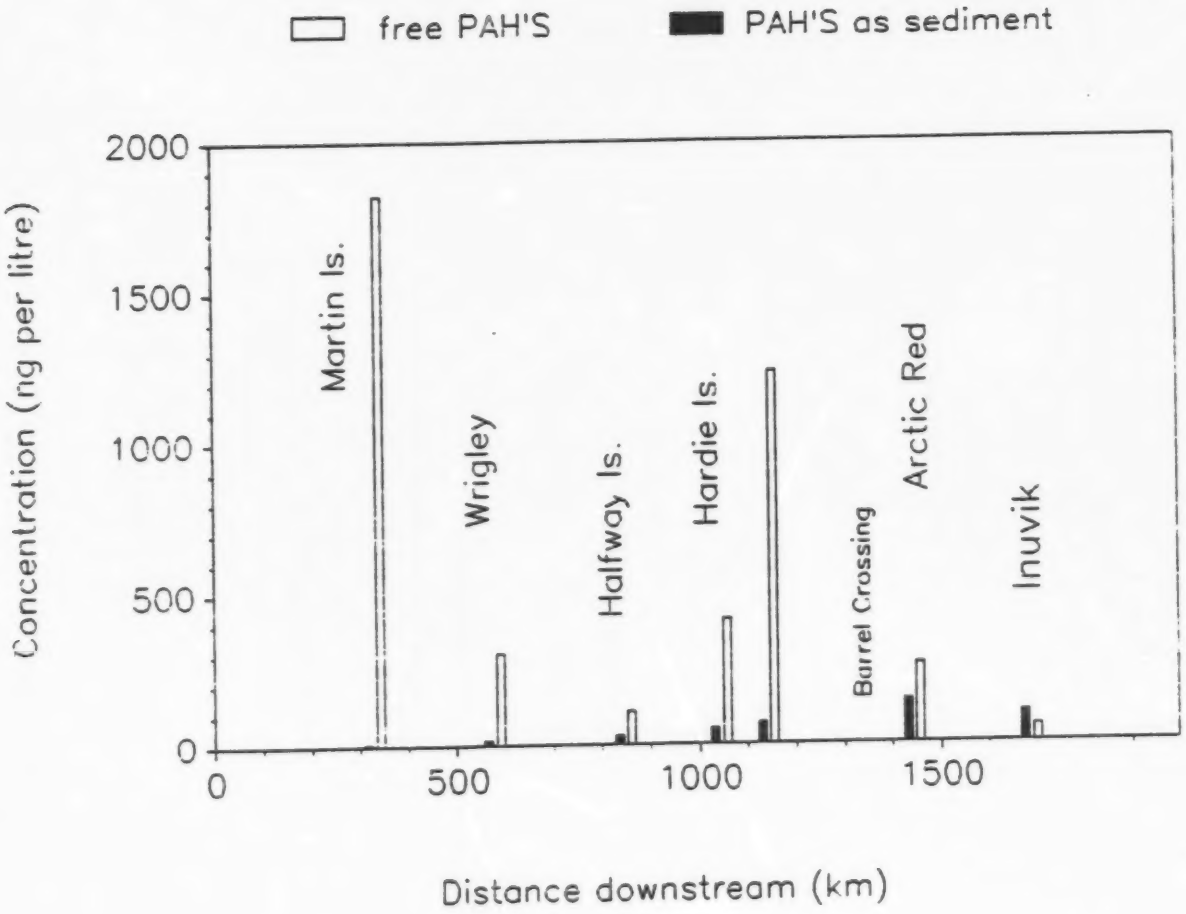


FIGURE 7 CONCENTRATION OF POLYCYCLIC AROMATIC HYDROCARBONS IN WATER AND SUSPENDED SEDIMENT: June 1986 (based on Nagy et al, 1987; data refer to total of 16 priority PAH species)

FIGURE 8 EXISTING AND PROPOSED SUSPENDED SEDIMENT SURVEY STATIONS

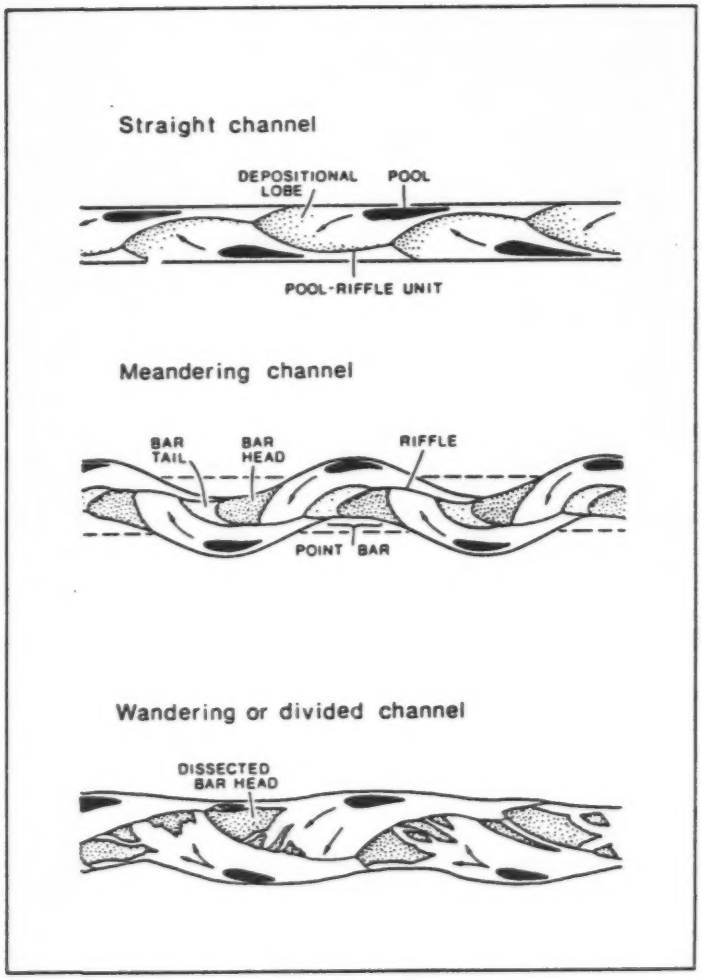


FIGURE 9 IDEALIZED MORPHOLOGY OF POOL-RIFFLE UNITS IN ALLUVIAL CHANNELS

(after Thompson, 1986)

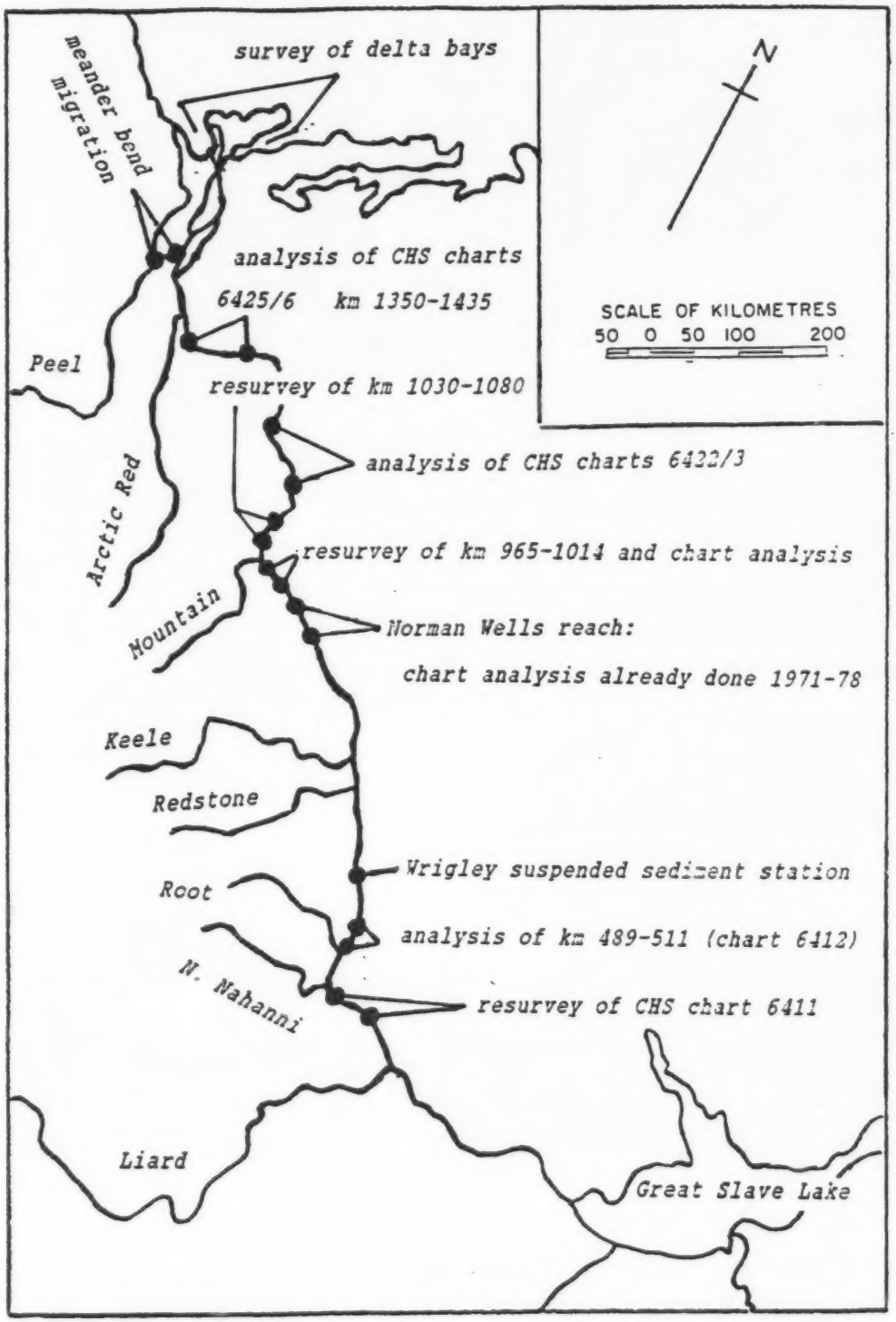
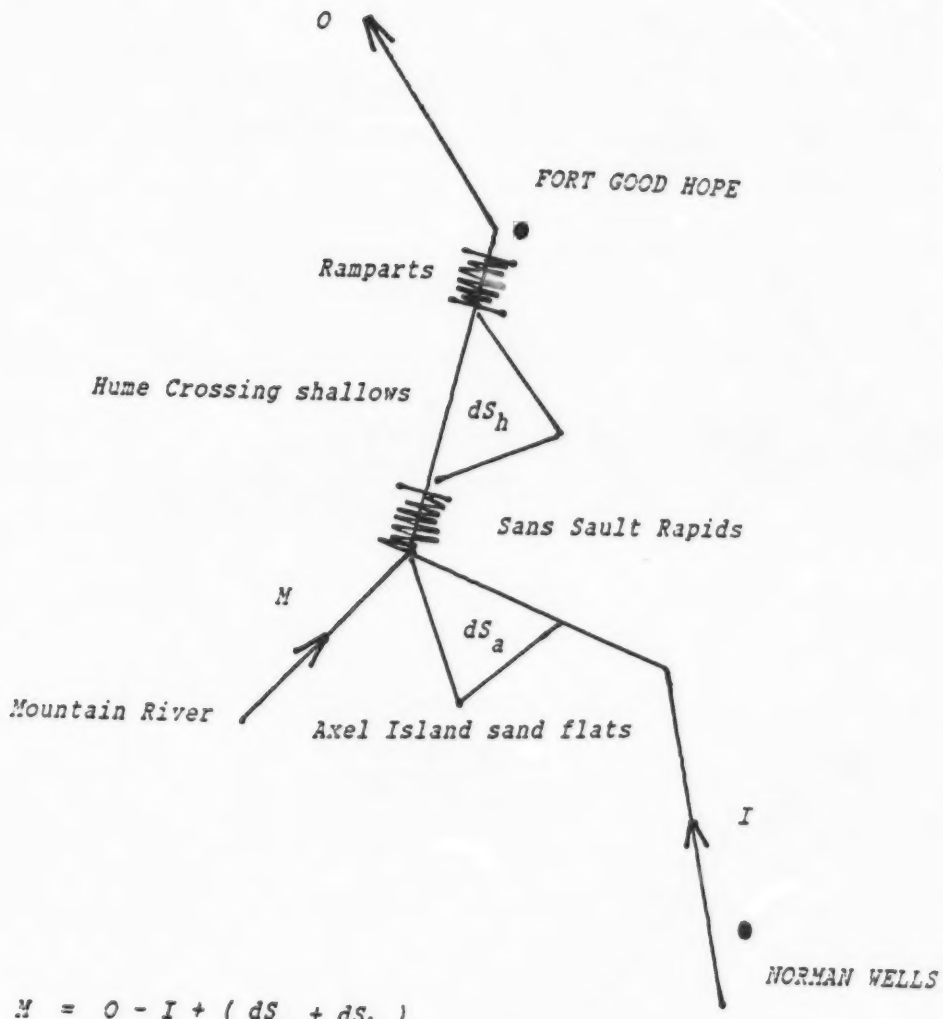


FIGURE 10 PROPOSED SAND BED MATERIAL LOAD SAMPLING PROGRAMME

FIGURE 11 CALCULATION OF CONTRIBUTION OF MOUNTAIN RIVER TO SANDY BED MATERIAL LOAD OF MACKENZIE RIVER BELOW FORT GOOD HOPE



$$M = O - I + (dS_a + dS_h)$$

where

M = contribution of Mountain River

O = sandy bed material load downstream of Fort Good Hope

I = sandy bed material load at Norman Wells

dS_a dS_h = aggradation in Axel Is and Hume reaches

FIGURE 12 LOCATION OF SIX ARTIFICIAL ISLANDS NEAR NORMAN WELLS (from Canadian Hydrographic Service chart 6419)

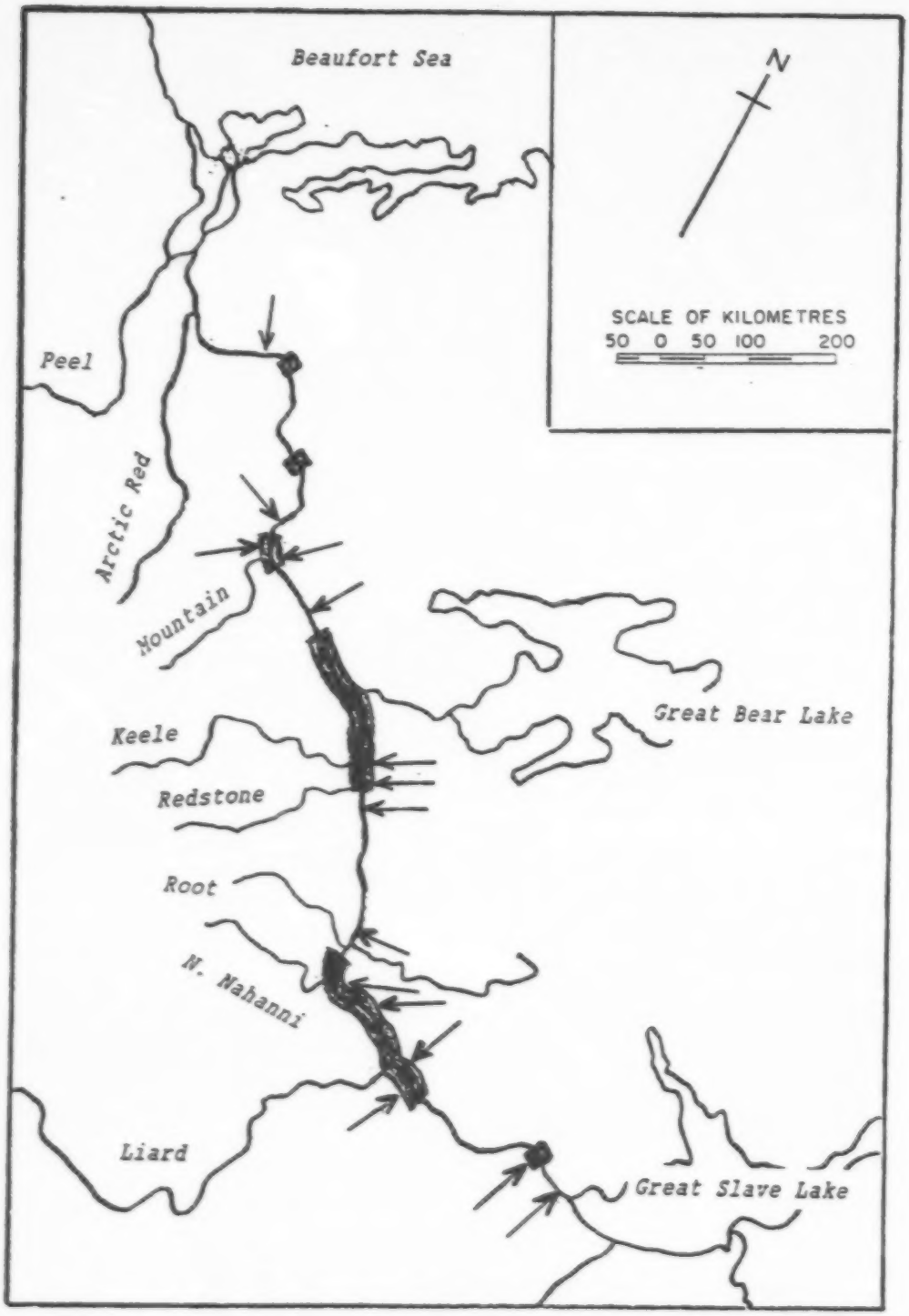


FIGURE 13 LOCATION OF POSSIBLE RIVERBED MINING AREAS AND PRIORITY DREDGING AREAS FOR NAVIGATION

thick strip denotes potential mining zone; arrowhead denotes priority navigation dredging

Based on EBA (1987), Acres (1987) and other sources